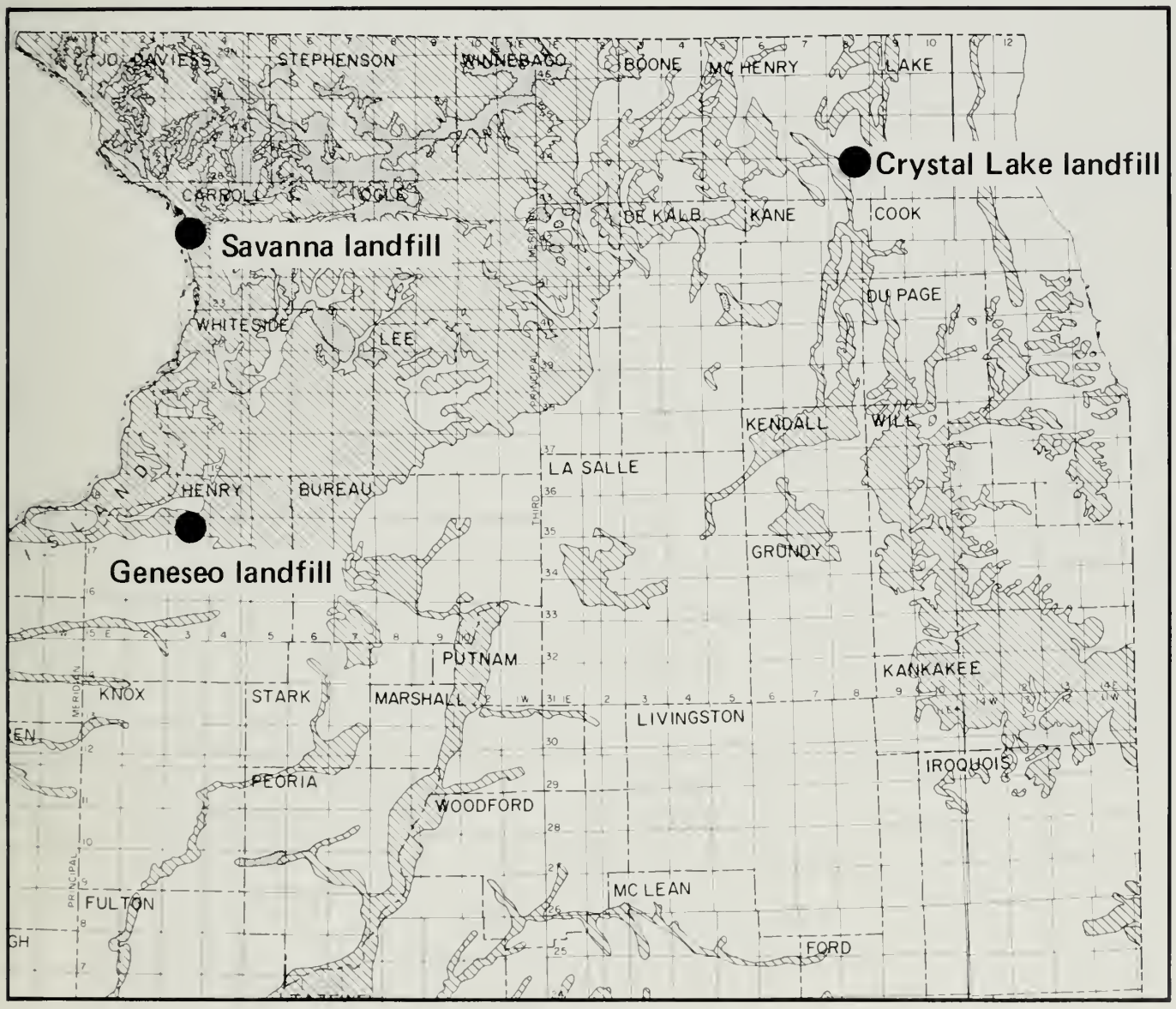
MONITORING OF LEACHATE MIGRATION IN THE UNSATURATED ZONE IN THE VICINITY OF SANITARY LANDFILLS

Thomas M. Johnson and Keros Cartwright



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STATE GEOLOGICAL SURVEY DIVISION, URBANA
Jack A. Simon, Chief

CIRCULAR 514
1980

Johnson, Thomas M.

Monitoring of leachate migration in the unsaturated zone in the vicinity of sanitary landfills / by Thomas M. Johnson and Keros Cartwright. — 1980.

82 p. : ill. : 28 cm. — (Circular / Illinois State Geological Survey ; 514)

1. Leachate. 2. Sanitary landfills—Pollution. 3. Waste disposal in the ground. 4. Water, Underground—Pollution. I. Title. II. Cartwright, Keros. III. Series.

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ABSTRACT

Numerous sites for solid-waste disposal are located in coarse-grained unsaturated materials because guidelines for siting and designing sanitary landfills have generally suggested or required that waste disposal take place above the water table. A project was undertaken to investigate the movement and quality of leachate in the unsaturated zone beneath landfills in Illinois and to evaluate methods of monitoring soil-moisture and ground-water conditions.

Three landfills representing different geologic environments and disposal practices were studied. Contaminant migration was monitored by means of observation wells and soil-water samplers (pressure-vacuum lysimeters) and by chemical analysis of soil samples. The chemical analyses of soil-moisture samples collected beneath and adjacent to the landfills provided valuable information on the extent of contamination from leachate. Migration of pollutants through the unsaturated zone was detected at each site even though monitoring wells appeared to be virtually unaffected.

The implications of waste disposal in unsaturated materials extend to the use of gravel drains and landfill liners for collecting or containing leachate. Although collection systems may function well under saturated conditions, they may be less effective under conditions of partial saturation.

A laboratory study was conducted to determine the validity of samples of highly contaminated landfill leachate collected with pressure-vacuum lysimeters. Samples from the lysimeters were very representative of the surrounding leachate composition of major ions.

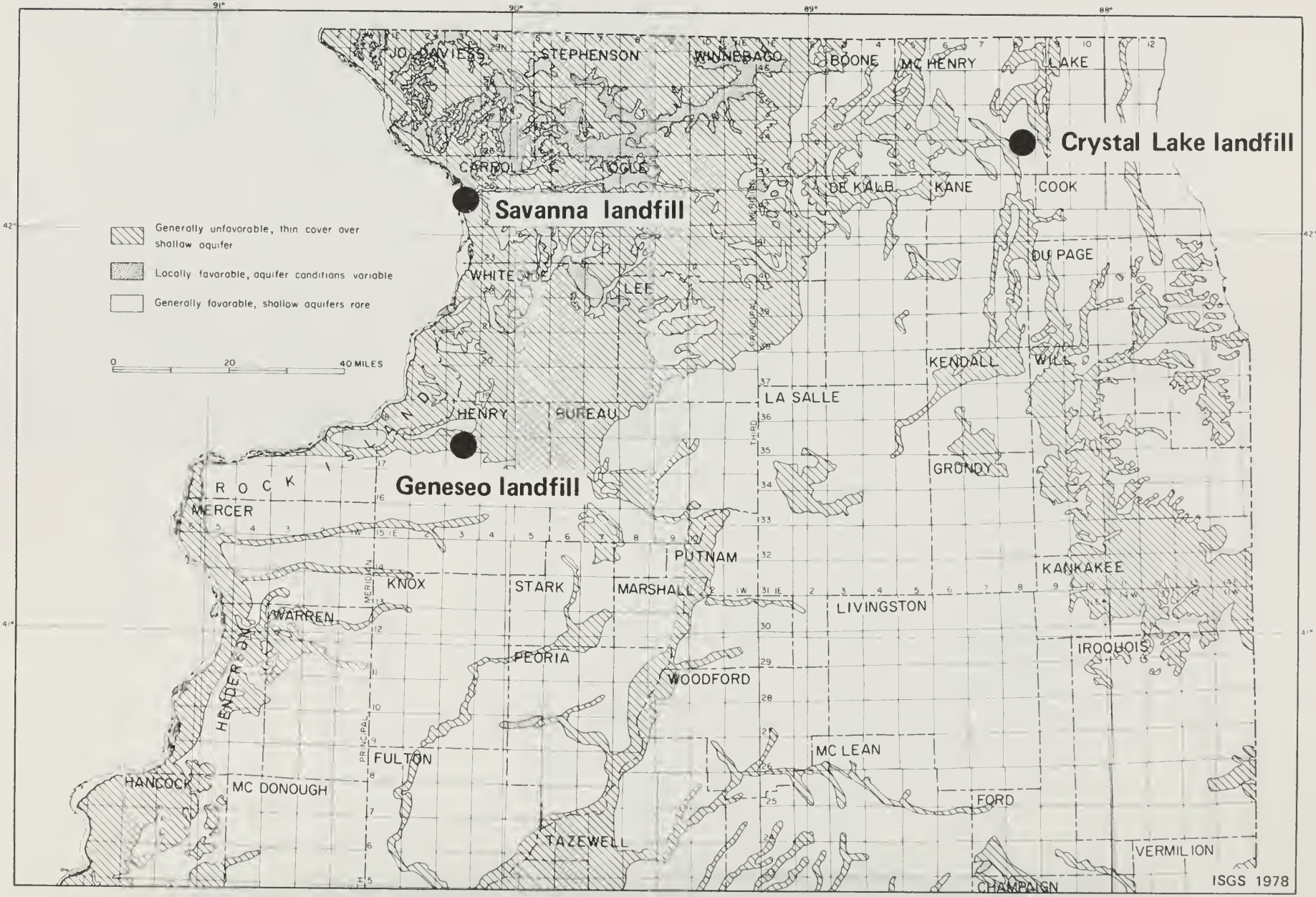


Figure 1. Geologic conditions relating to feasibility of sanitary landfills in the northern third of Illinois with locations of study sites.

PART I. FIELD STUDY

INTRODUCTION

Guidelines for the siting and design of landfills have generally suggested or required that waste disposal take place above the water table. It is generally assumed that the burial of refuse in the zone of saturation will increase the movement of ground water through the waste and hence will increase the production of leachate. Several studies have shown that in humid climates ground-water mounds will develop within landfills situated in fine-grained materials (Hughes, Landon, and Farvolden, 1971). In such cases, infiltration through the surface of the landfill maintains the production of leachate. Studies of landfills in northeastern Illinois have shown that, even with ideal soil conditions and cover compaction, one-third of the annual precipitation may infiltrate through the surface of the landfill. When cover materials are more permeable and differential settlement of the fill occurs, infiltration may increase greatly. In some cases, construction and maintenance of landfill cover of sufficiently low permeability to prevent infiltration and ground-water mounding may not be economically practical or even possible.

A recent survey of methods for protection of ground water from landfills indicated that 85 percent of all permitted sites for disposal of solid wastes in Illinois reportedly have bases located above the top of the zone of saturation (Clark, 1975). Only 15 percent of all permitted sites reportedly have bases situated below the water table either year-round or seasonally. Most landfill designs submitted to the Illinois Environmental Protection Agency (IEPA) for permit review are based on the concept of a "dry landfill," but many of the sites listed as being above the water table may actually be below the top of the zone of saturation. In Illinois, the relatively flat terrain underlain by fine-grained glacial materials causes shallow water table conditions, generally within 10 feet (3 m) of the surface. Favorable landfill sites are usually associated with very fine-grained materials that restrict ground-water movement. In these environments, monitoring wells may not actually reflect the top of the zone of saturation unless sufficient time is allowed for water levels to stabilize. Thus, a test boring or observation well may initially appear to be dry; but, given enough time, water levels may rise in the boring to approximately the top of the zone of saturation.

The emphasis upon waste disposal above the saturated zone has resulted in the location of numerous landfills in areas underlain by coarse-grained materials where deep, well-defined water tables are common. Although this may be an acceptable practice in arid climates where net infiltration is minimal, several workers (Apgar and Langmuir, 1971; and Gerhardt, 1977) have shown that in more humid areas, such as in Pennsylvania and Wisconsin, infiltration will produce leachate migration through unsaturated materials and can result in ground-water contamination.

Monitoring programs

Regulatory agencies have usually required that landfills use small diameter, plastic observation wells to monitor changes in quality of ground water. Unsaturated soils generally will not yield water to wells because moisture is held in the soil under tension by capillary forces. Thus, monitoring of the unsaturated zone beneath landfills has generally been neglected. Most field studies of the quality of ground water near landfills have involved collection of water samples only from monitoring wells screened in the saturated zone. By the time leachate contamination of ground water is detected in monitoring wells, corrective action is generally expensive and time-consuming.

Monitoring changes in water quality in the unsaturated zone provides information on the attenuation capabilities of unsaturated materials and the rates of ground-water movement, both of which are very difficult to estimate. Because the unsaturated zone beneath a landfill represents a buffer zone between refuse and potential aquifers, monitoring of this zone would allow for early detection of invasion of leachate. This would be applicable to sites that depend on natural processes for attenuation of leachate and especially to sites that are underlain by artificial liners to collect leachate for treatment. Methods for monitoring the unsaturated zone may also be applicable to areas where saturated materials of low permeability limit the use of standard monitoring wells.

The usefulness and reliability of methods for monitoring water quality in unsaturated materials have been demonstrated, such as using pressure-vacuum lysimeters, but their practical application to pollution control programs has been limited. Most states with ground-water monitoring regulations have required that observation wells be installed in the vicinity of solid-waste disposal sites, but have done little to monitor leachate migration or attenuation in the unsaturated zone. An exception is Minnesota where the Minnesota Pollution Control Agency has required the installation of soil-water samplers at several landfill sites.

Research into the movement and quality of leachate in unsaturated materials can result in better information relative to the hydrogeologic criteria used for the selection of solid waste disposal sites. It can also aid in the development of more effective, and possibly less expensive, monitoring systems for ground water.

DESCRIPTION OF THE PROJECT

Selection of sites

Three sanitary landfill sites in northern Illinois (fig. 1) were selected for investigating the movement and quality of leachate in the unsaturated zone and for evaluating methods of monitoring soil-moisture quality. All three sites are in unsaturated materials above usable aquifers and reflect a variety of geologic environments and disposal practices. Sites were to be chosen in both coarse-grained (sandy) soils and fine-grained (silty) soils. Many potential sites in fine-grained glacial till were eliminated because ground water was too shallow (less than 10 feet [3 m]) or because a ground-water mound was present within the landfill. Figure 1 shows the locations of the three landfill sites with respect to the geologic conditions affecting the feasibility of sanitary landfills in northern Illinois.

Originally, the project was designed to instrument several new landfill sites to document the history of leachate migration. It became apparent that the limited length of the study (2 years) and the lack of appropriate new landfill sites required that only existing landfills be studied. It was possible, however, to instrument new portions of the Savanna landfill to determine the effectiveness of lysimeters installed directly beneath a landfill prior to waste disposal.

Methods

The investigation at each of the landfill sites initially consisted of the following stages:

1. Boring and sampling of geologic materials;
2. Installation of monitoring devices in borings;
3. Sampling of ground water, soil moisture, and related information (water levels, etc.).

Drilling at each site was generally accompanied by continuous split-spoon sampling of the geologic materials to determine the detailed stratigraphy beneath each landfill. Cores and samples were logged in the field and were returned to the laboratory. The soil samples were carefully described to establish the general characteristics of each geologic unit and were then submitted for analysis of physical properties including grain-size distribution, clay mineralogy, water content, and hydraulic conductivity. Data for each boring are listed in the appendixes. Samples from at least one hole beneath each site were also taken during drilling for chemical analysis, were bottled, and immediately were returned to the laboratory.

MONITORING TECHNIQUES

Monitoring the saturated zone

The study of ground water in the saturated zone involves the use of several methods to monitor water quality and determine the hydrogeologic framework. These methods generally include observation wells and a variety of surface and subsurface geophysical techniques. The monitoring of ground-water quality in the saturated zone near landfills requires the careful collection of representative samples of ground water from properly constructed wells. Monitoring techniques applicable to the saturated zone have been discussed in numerous publications, most recently by Everett et al. (1976) and Fenn et al. (1977).

Installation of monitoring wells

Observation wells were installed at each landfill site to complement the existing monitoring well systems. Installation data for each monitoring well are presented in appendix 1. Most of the wells were installed by the Illinois State Geological Survey (ISGS) by using hollow augers drilled to the desired depth. Wells generally consisted of either 1¼-inch (3.2 cm) or 1½-inch (3.8 cm) diameter PVC plastic pipe with 1¼-inch (3.2 cm) diameter plastic well screens. The borehole surrounding each well above the screen was backfilled with bentonite clay and soil material to provide an effective seal. Two new observation wells were installed at Crystal Lake, four at Savanna, and six at Geneseo. In addition to these wells, other wells in the vicinity (such as domestic and municipal) were used to monitor local fluctuations in levels and quality of ground water.

Monitoring the unsaturated zone

Water movement above the water table usually occurs in the unsaturated state; soil water exists under tension by capillary forces at less-than-atmospheric pressures. The physics of unsaturated flow has been extensively studied by soil physicists, agricultural engineers, and others. In recent years, the concept of unsaturated flow has become increasingly important to hydrogeologists, especially with regard to studies of the impact of waste disposal on ground water.

During infiltration, gravitational water in excess of that held by capillary and molecular forces (field capacity) percolates downward through the unsaturated zone toward the water table. Temporary zones of saturation may develop above materials of low permeability, creating a perched water table. Saturated conditions may also occur above the boundary between materials of greatly different textures,

such as where fine-grained material overlies coarse sand or gravel. This concept was demonstrated in laboratory studies by Palmquist and Johnson (1962) and Corey and Horton (1969).

Numerous techniques have been developed for monitoring the movement and quality of water in the unsaturated zone. These techniques generally determine the water content of the materials, the rate of moisture flow, and chemical changes of water interacting with the soil. Extensive discussions of these methods, including their relative advantages and disadvantages, are presented by Richards (1949), Everett et al. (1976), and Fenn et al. (1977).

Methods for monitoring the movement of water in the saturated zone are generally not applicable to the unsaturated zone. Water will generally not enter a well because soil-moisture pressures are negative. Thus, special methods such as tensiometers, psychrometers, and neutron-moisture logging must be used to obtain information about soil-moisture pressure and water content and to measure the soil-moisture flux and hydraulic conductivity.

The sampling of water from unsaturated materials is necessary to determine changes in the chemical quality of soil mositure. These chemical changes are the result of several interacting factors such as: precipitation, dissolution, ion exchange, adsorption, and oxidation-reduction. Sampling designed to monitor these changes at any depth is basically limited to two methods: (1) To determine the quality of soil moisture, saturation extracts are obtained from soil samples. (2) To monitor the effects of soil-water interactions with the soils, a chemical analysis is made of the soil materials themselves.

An alternative method of sampling soil-moisture quality is the use of porous ceramic cups similar to those used in tensiometers. These porous cups reach equilibrium in the soil with surrounding soil moisture; the application of a vacuum causes soil moisture to flow into the cup. Whereas soil sampling requires repeated drilling for extended analyses, soil-moisture sampling using suction or pressure-vacuum lysimeters allows repeated sample collection. A primary purpose of this project was to evaluate the use of soil-moisture samplers, or pressure-vacuum lysimeters as they are called, for monitoring the quality of soil moisture beneath landfills.

Development of pressure-vacuum lysimeters. Porous ceramic materials have long been used as a semi-permeable membrane to extract water from soil to study the quality or energy status of soil moisture. Briggs and McCall (1904) first suggested the use of ceramic cups for extracting moisture from unsaturated soil. This method included the use of a ceramic cup attached to a tube extending to the surface where a vacuum applied to the tube resulted in the collection of a sample of soil moisture. This device was later tested by Krone, Ludwig, and Thomas (1951), and Wagner (1962) evaluated a commercial version of the ceramic-cup

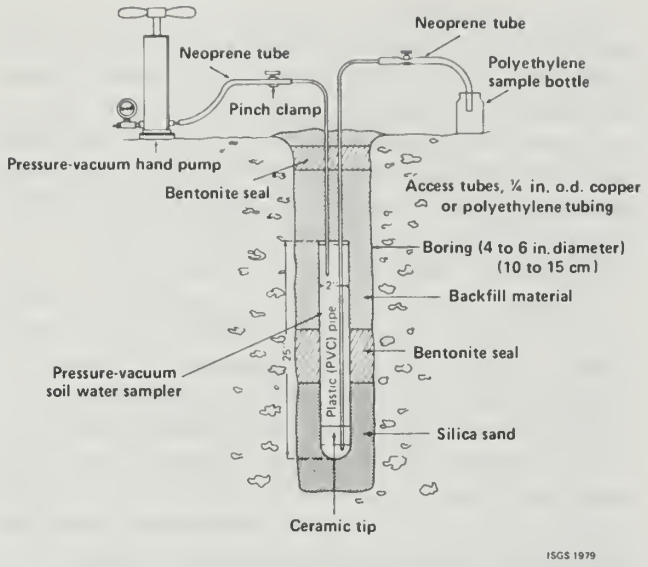


Figure 2. Typical installation of pressure-vacuum lysimeter.

soil-moisture sampler that was similar to that used in this project. Wagner described the use of a ceramic cup attached to a short length of plastic pipe that held a fluid volume of 100 mL with a single access tube extending to the surface. Although this design was similar to that used in subsequent studies, the use of a single access tube limited the ability to sample to relatively shallow depths.

The basic design was modified during several studies in Pennsylvania designed to monitor the effects of the infiltration of waste water and the migration of landfill leachate (Parizek et al., 1967; Lane and Parizek, 1968; Parizek and Lane, 1970; and Apgar and Langmuir, 1971). Sampling at greater depths could be done by the use of two access tubes and a ceramic cup attached to a sample accumulation chamber of PVC pipe which could hold approximately 1 liter. With this design (fig. 2), a partial vacuum is applied to the sampler through one of the access tubes, which is then clamped shut. Soil moisture held under tension moves into the sampler under the potential gradient created by the vacuum, and water gradually accumulates. When the vacuum is released and pressure is applied to one access tube, the accumulated water sample is forced to the surface through the other access tube. In the studies of landfills in Pennsylvania, several pressure-vacuum (suction) lysimeters were installed in individual boreholes at depths to 55 feet (16.8 m). The movement and attenuation of leachate were monitored by standard indicators of water quality; Apgar and Langmuir (1971) concluded that improperly designed landfills located above the water table in permeable materials can result in serious ground-water pollution.

Wood (1973) described a modification of the lysimeters used by Apgar and Langmuir; the modification would allow the sampling of water from any depth. The use of a check valve prevents pressurization of the porous cups;

in deeply placed lysimeters, pressures in excess of one atmosphere in the sampler would force the water sample back through the cup rather than to the surface. Further refinements and evaluations of soil-moisture samplers have continued; Wengel and Griffin (1971) developed automated remote sampling techniques and Levin and Jackson (1977), a comparison of ceramic cup and cellulose acetate hollow fiber soil-moisture samplers.

Lysimeters have been used to trace pollution from septic tanks (Manbeck, 1975; and Beehler and Moore, 1979), cesspools (Nassau-Suffolk Research Task Group, 1969), synthetic detergents (Department of Water Resources, 1963), and colliery spoil heaps (James, 1974).

More recent applications have included the use of suction lysimeters to monitor the quality of water in the unsaturated zone at depths to 108 feet (33 m) below artificial recharge sites in Texas (Wood, 1978). Krothe and Parizek (1979) used lysimeters to evaluate the geochemistry of soil water beneath the flood plain and channel of an influent stream in a carbonate terrain.

An investigation of several landfills in Wisconsin (Gerhardt, 1977), similar to and contemporaneous with our Survey study, was recently conducted to generate data on the attenuation of leachate in the unsaturated zone. Three operating landfills were instrumented with suction lysimeters installed in and beneath the refuse. Leachate migration and attenuation were monitored at each site. Anomalous changes observed in the quality of soil-moisture leachate were attributed to complex soil-leachate interactions and variability in soil-moisture status. Gerhardt concluded that the development of uniform criteria for the siting of landfills above the water table is limited by the complexity of water-soil-leachate interactions, and additional information must be obtained to determine the attenuative capacity of unsaturated soils. Michel (1976) investigated ground-water pollution at two landfills in South Carolina and found that trends in soil-moisture quality indicated the movement of a slug of highly contaminated leachate through the unsaturated zone into the underlying aquifer.

With the increased usage of porous, ceramic-cup samplers to describe the quality of soil moisture, investigations have been conducted in two additional areas: (1) the calculation of soil-moisture regimes in the vicinity of porous cup samplers (van der Ploeg and Beese, 1977; and Warrick and Amoozegar-Fard, 1977) and (2) the validity of chemical analyses of water samples collected with porous ceramic cups.

The validity of soil-moisture samples as representative of actual soil-moisture quality was initially addressed by Briggs and McCall (1904) and other early workers who saw no measurable changes in the concentrations of soil solutions passed through washed ceramic cups. Subsequent studies, however, have indicated that ceramic cups can influence the chemical analyses of samples of soil moisture. Some elements originally present in the cups may be dissolved and certain constituents may be adsorbed or screened by the ceramic material. Grover and Lamborn (1970) found that ceramic cups contributed excessive amounts of Ca, Na, and K to extracted soil moisture having low concentrations of solutes and the significant amounts of P were adsorbed on the ceramic cups from these solutions. Leaching of the cups with dilute HCl reportedly reduced Na and K contamination and P adsorption to acceptable levels. The validity of bacteriological analyses of soil-moisture samples from porcelain-cup samplers was investigated by Dazzo and Rothwell (1974). They found that large-scale screening and adsorption of fecal coliforms by ceramic cups with a pore size of 3 to 8 μm invalidated their use for the analysis of fecal coliform. Lane (1969) stated that the effective pore diameter of the porous ceramic cup is approximately 1 μm or less. As Apgar and Langmuir (1971) suggested, even a diameter of 1 μm allows most colloidal particles to enter the sampler; however, some particulate matter such as bacteria may be filtered out, as was indicated by Dazzo and Rothwell (1974).

Extensive laboratory and field tests of the validity of NO_3-N and P analyses of soil-moisture samples collected with ceramic cups were made by Hansen and Harris (1975). Substantial sample variability and bias were found. Sample variability was influenced by sampler intake rate, plugging, sampler depth, and type of vacuum systems (which simulated different sizes of samplers). Sources of sample bias included sorption, leaching, diffusion, and screening of P by the cup walls. They concluded that the combination of sample variability and bias and the many factors which affect sample concentration makes the interpretation of sampler data difficult. They suggested that the extreme versatility and usefulness of the method for some purposes offset these limitations and require that solutions to these problems be found. Zimmerman, Price, and Montgomery (1978), in a laboratory comparison of porous ceramic samplers and porous Teflon® (PTS) samplers, found substantial variability in concentrations of NH_4, and PO_4 in samples from the ceramic samplers. They also found clogging to be a problem with ceramic samplers. Due to the inert nature of the PTS samplers, virtually no variability in concentrations was found and there was no clogging. The use of porous PTS, however, is limited to sampling saturated media. Montgomery, Zimmerman, and Price (1979) used porous PTS samplers to determine the nutrient content of anoxic pore waters in saturated estuarine sediments. More recent research by Levin and Jackson (1977) indicated that concentrations of Ca, Mg, and PO_4-P in soil solutions were unaltered by ceramic-cup samplers and that clogging was not a problem. Possible screening of NO_3 was indicated, however. Laboratory experiments conducted during this study (see Part II) determined that representative samples of highly mineralized landfill

leachate could be collected with pressure-vacuum lysimeters.

Pressure-vacuum lysimeter installation and operation. The pressure-vacuum (suction) lysimeters (Model 1920) used in this study were obtained from Soil Moisture Equipment Corporation, Santa Barbara, California.* A typical lysimeter installation is illustrated in figure 2. The lysimeter device which holds 1 liter of water, consists of a plastic cylinder 25 inches (64 cm) long and 2 inches (5 cm) in diameter, having a porous ceramic cup, 2.5 inches (6 cm) in length. An envelope of silt-sized, powdered quartz (Silcosil or silica sand) was emplaced around the ceramic cup to establish uniform continuity with surrounding soils.

In this study, a portable hand pump that could produce a vacuum was used to evacuate the samplers. The hand pump was also used to apply air pressure to one access tube to force the water sample to the surface through the discharge tube that extends to the base of the sampler. Gas pressure (argon, nitrogen, CO_2, propane, etc.) could also have been used for sample collection.

The suction lysimeters were placed at varying depths beneath each site, one to three lysimeters in each borehole. The boreholes were made by three methods: (1) hollow-stem auger, (2) solid auger, and (3) hand auger. Initial attempts to install lysimeters through 3-inch (7.6 cm) inside diameter (I.D.) hollow-stem augers proved unsuccessful as the Silcosil and bentonite bridged within the augers when emplacing the sampler. All lysimeters were subsequently installed in 4- to 8-inch (10.2 to 20.3 cm) open boreholes following the removal of augers. In all cases, the boreholes remained temporarily open at least to the depth of the water table. Granular and pelletized bentonite was placed above and between lysimeters to prevent leachate channeling, and the holes were backfilled with the original soil materials. Installation data for each lysimeter boring are presented in appendix 2. The relative positions and depths of lysimeters at each landfill are shown in cross sections of each site.

Water sampling

Approximately 102 soil-moisture samples were collected from the suction of lysimeters during a sample collection period that ranged from three days to three months. Approximately 50 ground-water and surface-water samples were also collected from monitoring wells or streams adjacent to the sites. Ground-water samples were obtained after attempts to remove the accumulated water in the well. The well samples were filtered in the field by using Whatman No. 42 filter paper. Soil-moisture samples from the suction lysimeters are effectively filtered as they pass through the silica sand and the ceramic tip and, therefore, were not filtered. A portion of each water sample was acidified with concentrated hydrochloric or nitric acid, and a similar portion was not acidified. Both portions were put in polyethylene bottles and returned to the laboratory where they were refrigerated prior to analysis. Most of the samples were analyzed by the Illinois State Geological Survey. A few water samples were analyzed by the Illinois Environmental Protection Agency (IEPA) and the Illinois State Water Survey (ISWS).

*Mention of trade names in this paper does not imply endorsement by the Illinois State Geological Survey or sponsoring agencies.

Soil and water chemical analysis

Forty soil samples were analyzed by the Illinois State Geological Survey for the following constituents: Na, Ca, Zn, Fe, Pb, Hg, K, SO_4, pH, and cation exchange capacity (CEC). The results are presented in appendix 3. The data for each element represent the total concentration in the soil sample.

Chemical analyses were made of soil-moisture samples from the lysimeters in addition to periodic samples of ground water and surface water in the vicinity of each site. The results are presented in appendixes 4 and 5. Immediately following collection of samples, field measurements were made of temperature, pH, Eh, specific conductivity, and alkalinity. Qualitative field observations were also made of color, turbidity, and odor. Laboratory analyses routinely performed by ISGS included the following: Na, Ca, Mg, Zn, K, Fe, Pb, Hg, Cl, SO_4, NO_3-N, NH_4-N, hardness, pH, total dissolved solids (TDS) and chemical oxygen demand (COD). Analyses performed by the IEPA included several additional constituents: B, Ba, and Mn. Analytical methods are described in appendix 6.

REGIONAL GEOLOGY

The preglacial bedrock surface in Illinois varies in age from Pennsylvanian to Cambrian. The three study areas (fig. 1) are underlain by a variety of bedrock types ranging from Pennsylvanian shale at Geneseo, to Ordovician dolomite at Savanna, and Silurian dolomite at Crystal Lake.

The Crystal Lake site is located in northeastern Illinois in the rough, irregular terrain of the Wheaton Morainal Country. The landfill area is underlain by water-laid sand and gravel, till sheets of Wisconsinan age, and Wisconsinan loess and silts. The Geneseo site is located in northwestern Illinois on a low upland immediately adjacent to the Green River Lowland, a broad area underlain by massive deposits of sand and gravel. The site is situated in an area of large sand dunes and is underlain by till units probably of Illinoian age, Illinoian sand and gravel, Wisconsinan water-laid silt and sand deposits, and Wisconsinan wind-blown sand and silt. The Savanna site is located in the Wisconsin Driftless Section of extreme northwestern Illinois on the floodplain of the Mississippi River and is underlain by recent alluvial materials over Wisconsinan glacial outwash.

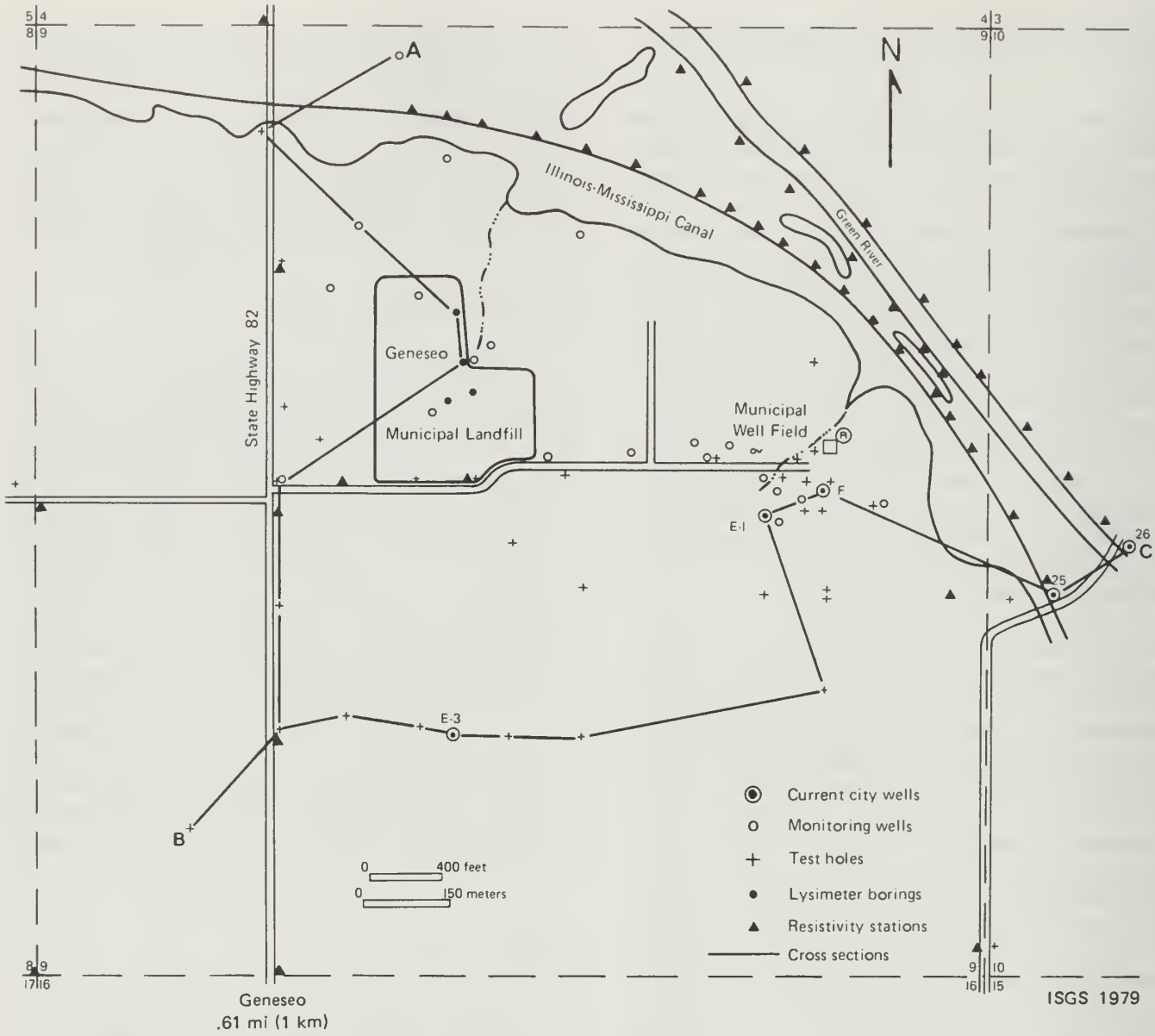


Figure 3. Map of general area of Geneseo landfill and water well field.

GENESEO MUNICIPAL LANDFILL

DESCRIPTION OF SITE

The Geneseo municipal landfill is located in Henry County in northwestern Illinois in NW¼ Sec. 9, T. 17 N., R. 3 E. (fig. 1). Operations began originally as an open burning dump in the eary 1900s but operated as a sanitary landfill from 1967 to 1975. The landfill is on an upland consisting of a massive sand dune that is adjacent to the valley of the Green River. The landfill is approximately 1,000 feet (300 m) south of the Illinois-Mississippi Canal and the Green River, which flow toward the Rock River to the west (fig. 3). The elevation of the landfill and the surrounding upland ranges from approximately 635 feet (194 m) to 675 feet (206 m) above sea level, and the broad lowland to the north has an elevation of about 600 feet (183 m).

Portions of the landfill site have been excavated as a source of fine sand. During the early history of the site, from about 1900 through the 1950s, the southern portion of the site, adjacent to the road, was excavated and filled from west to east. From the 1950s to 1967, refuse was scattered and burned over the southeast portion of the site. In 1967, sanitary landfill procedures were initiated. In the northern half of the site, refuse was deposited in trenches excavated in fine to medium sand to depths of approximately 20 feet (6 m). Intermediate cover, when it was applied, consisted of sand. The fill material consisted almost entirely of general household refuse from Geneseo and the immediate vicinity. The extreme northern edge of the landfill was used for the disposal of wood debris. Figure 4 shows the general successsion of filling and the locations of monitoring wells and lysimeter borings at the site.

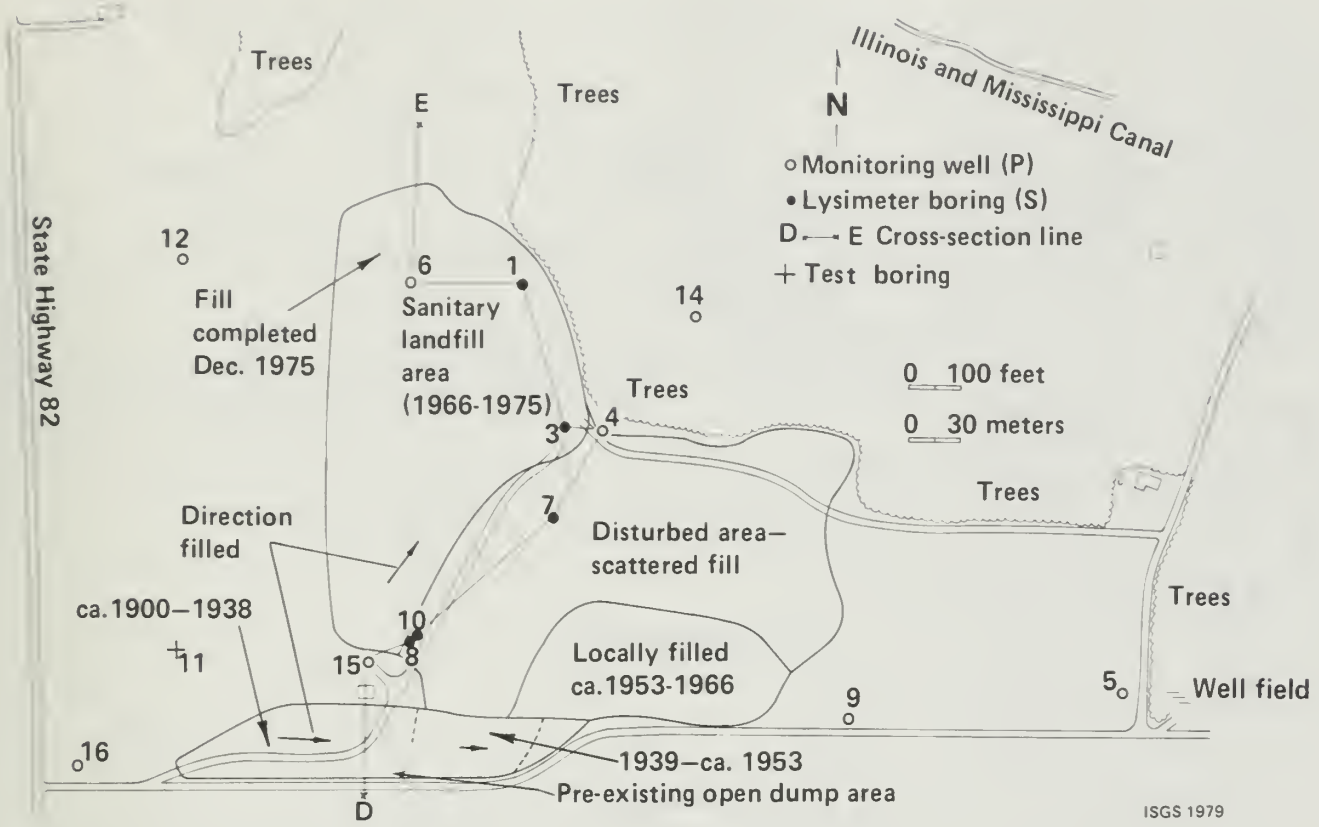


Figure 4. Plan view of the Geneseo landfill showing the general sequence of filling and locations of monitoring wells and lysimeter borings (base from McClure-Dunkirk Engineering, Inc., 1975).

By 1902 the city of Geneseo had outgrown its first public water supply, an artesian well near the center of town finished in Cambrian sandstone at a depth of 2,200 feet (670 m). A series of springs and shallow wells was then developed for a new water supply on land leased by the city approximately 1,800 feet (550 m) east of the operating city dump. Figure 3 shows the location of the well field in relation to the landfill. The springs were abandoned by 1930; but, by 1946, a total of 11 shallow wells 10 to 25 feet (3 to 8 m) deep had been installed east of the landfill. In 1958, an additional well (E-3) was drilled approximately 1,500 feet (450 m) south of the landfill into sand and gravel at a depth of 65 feet (19.8 m) and two wells were drilled in the lowland east of the site adjacent to the Green River. The shallow wells and well E-3 have been the focus of much controversy involving the landfill.

The landfill was closed in 1975 following the suspected contamination of several shallow municipal wells. Final cover, consisting of fine to medium sand, was applied in 1976, and the older portions of the site were regraded; the disturbed area was then seeded. Sparse weeds and grasses cover much of the site although portions still remain bare. Small gullies have eroded in the loose sand cover on the northern part of the site, although the permeable nature of the cover material does not promote much runoff except during heavy storms.

GEOLOGY

The Geneseo landfill is situated on a large sand dune on the edge of the Green River Lowland. The landfill is underlain by a succession of sand, silt, glacial till, and sand and gravel, ranging from 50 feet (15 m) to possibly 140 feet (43 m) in thickness, overlying shale bedrock.

The cross sections in figure 5 illustrate the general sequence of materials beneath the landfill and well field. Figure 6 is a cross section of the materials directly beneath the refuse and shows a portion of the monitoring well and lysimeter network. The extensive deposit of uniform, fine- to medium-grained sand that immediately underlies the refuse contains several thin, discontinuous silt lenses. The entire sand area is underlain by a layer of fine-grained Illinoian glacial till, 3 to 26 feet (1 to 8 m) thick, which separates the overlying refuse and dune sand from the underlying medium- to coarse-grained sand and gravel aquifer. The glacial till may be thin and discontinuous near the edge of the upland and in the vicinity of the well field east of the landfill; however, deposits of laminated silt and silty clay overlie the shallow sand and gravel aquifer to the east of the landfill site.

Descriptions of soil samples from the borings made during this study are included in appendix 7; laboratory data from selected borings are presented in appendix 8. Table 1 summarizes the texture, mineralogy, and cation exchange capacity of each unit.

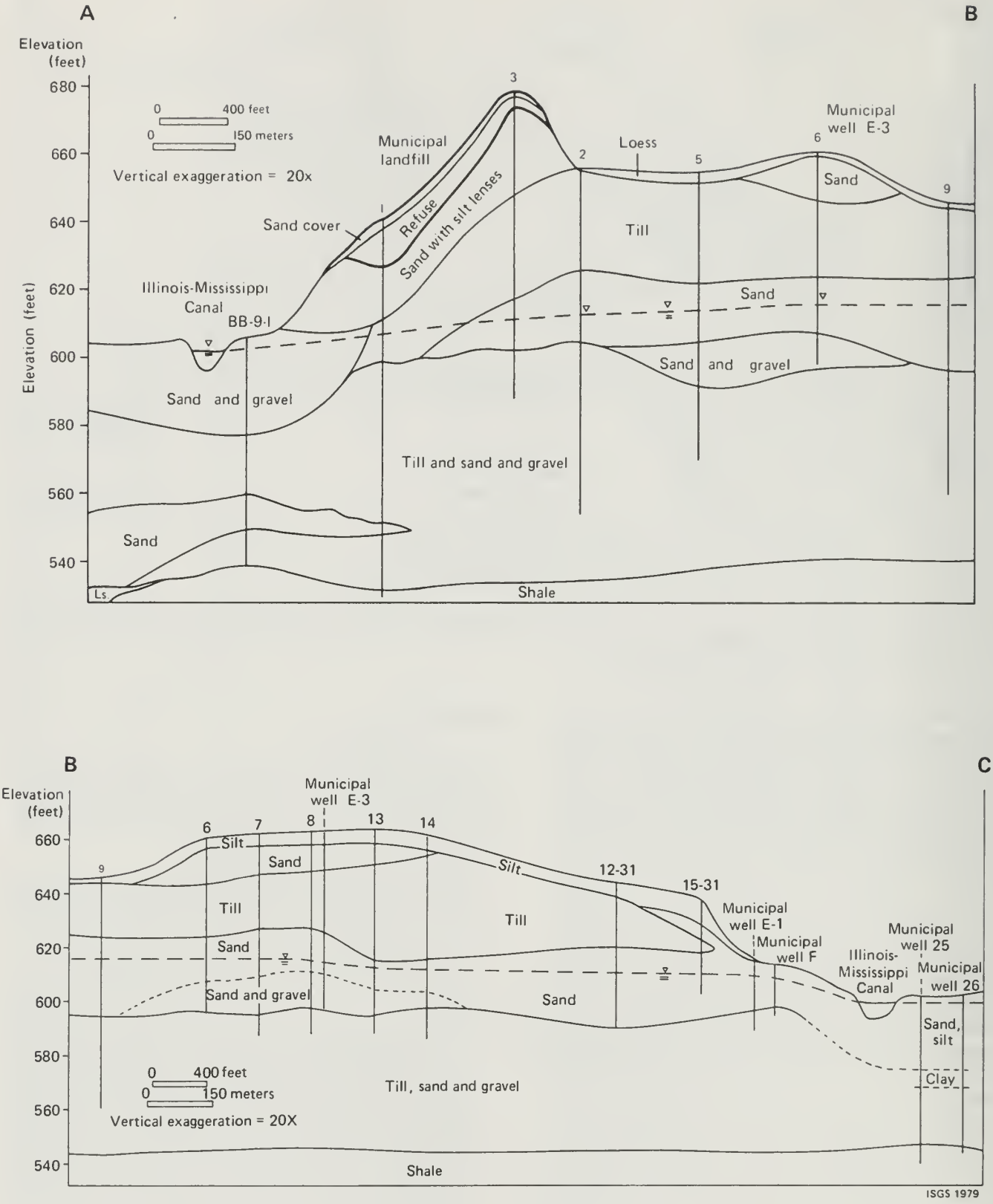


Figure 5. North-south A-B (top) and east-west B-C (bottom) cross sections of the Geneseo landfill and vicinity showing the topography and general geologic sequence.

TABLE 1. Mean texture, clay mineralogy, and range of cation exchange capacity (CEC) of materials beneath the Geneseo landfill.

Material	Texture[a]				Clay mineralogy[b]			
	Gravel (%)	Sand (%)	Silty (%)	Clay (%)	EX (%)	I (%)	C + K (%)	CEC[c]
Sand	0	90	5	5	55	33	12	0.6-2.6
Silty sand to sandy silt	0	48	40	12	57	31	12	1.8-8.4
Silt	0	9	72	19	63	26	11	1.3-8.9
Till	4	20	36	44	10	78	12	2.2-10.1

[a]Gravel > 2 mm; sand, 2 to 0.0625 mm; silt, 0.0625 to .0039 mm; clay, < .0039 mm.
[b]Ex = expandables; I = illite; C + K = chlorite plus kaolinite.
[c]Milliequivalents per 100 g dry soil.

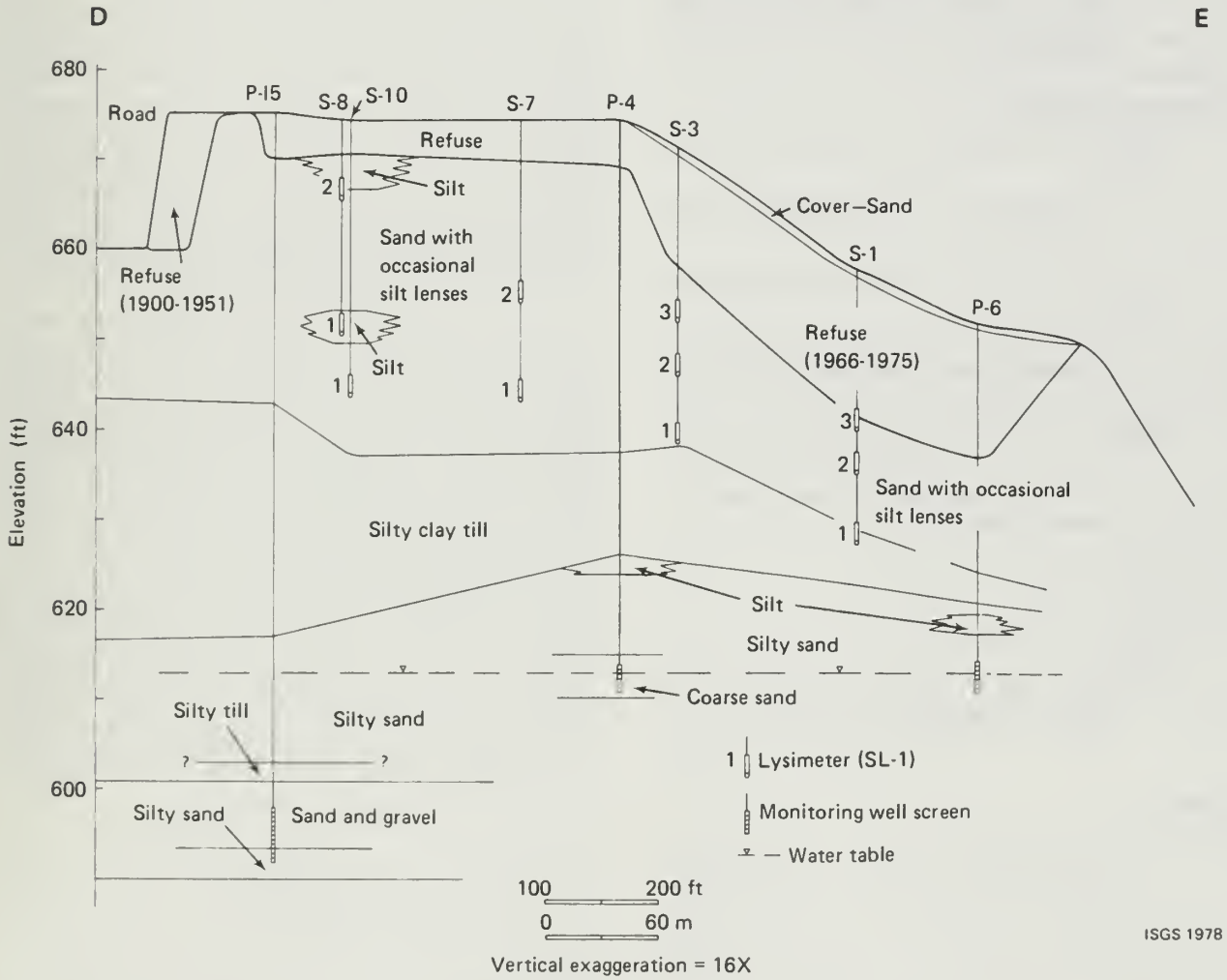


Figure 6. Cross section D-E of the Geneseo landfill and underlying materials showing a portion of the monitoring well-lysimeter network.

A brief description of each stratigraphic unit follows:

Quaternary System

Pleistocene Series

Holocene Stage

Parkland Sand (6.5 to 37 feet [2 to 11 m] thick)

Wind-blown sand, uniform, very fine- to medium-grained, interbedded with occasional lenses of silt and silty clay. Lower portion may consist of water-laid material. Generally calcareous below a depth of 15 feet (4.5 m); but locally leached to a depth of 25 feet (7.6 m). Upper surface has been disturbed, but it is locally overlain by silty material and poorly developed Modern Soil.

Illinoian Stage

Glasford Formation (3 to 26 feet [1 to 8 m] thick)

Gray, silty, clayey glacial till; occasional lenses of silt; generally calcareous to its upper surface. No evidence of Sangamon Soil. Isolates surficial sand above from underlying sand and gravel aquifer.

Illinoian Stage and older

Outwash silt and sand (15 to 30 feet [5 to 9 m] thick)

Interbedded fine to medium sand, silty sand, and silt deposits. Calcareous.

Outwash sand and gravel (10 to 15 feet [3 to 4 m] thick)

Medium to coarse, clean sand and gravel. Calcareous. Locally present. Major aquifer.

Glacial till, silt and sand and gravel (50 feet [15 m] thick)

Reported in older borings, not encountered during this study; may be thin or absent to south of lowland.

Pennsylvanian System

Shale bedrock (possible less than 50 feet [15 m] thick)

Fine-grained shale with thin beds of sandstone, coal, and limestone. Thins to north. Non-aquifer.

Silurian System

Niagaran Series

Dolomite bedrock, locally well fractured. May underlie drift north of landfill. Minor aquifer.

This is the general succession of materials beneath the upland area and the landfill north of Geneseo. The broad lowland immediately north of the landfill consists of a thick sequence of silt and gravel deposited in a broad, preglacial bedrock valley.

HYDROGEOLOGY

To evaluate the hydrogeologic setting of the site, six newly installed observation wells (fig. 4) and several pre-existing wells were monitored. Installation data for each well are included in appendix 1.

Water levels in the monitoring wells ranged from approximately 25 feet (7.6 m) to 60 feet (18.3 m) below the base of the refuse. Figure 7 shows the changes in static water levels and the average monthly precipitation during the study. Water levels declined slowly after April 1976 with very little fluctuation. Water levels apparently have declined in response to reduced precipitation and continued ground-water withdrawals.

Regional data suggest that ground-water flow is toward the Illinois-Mississippi Canal and the Green River. Water levels in well P-6, approximately 1 foot (0.3 m) greater than those in wells P-4 and P-12, indicate that a small, ground-water mound may be present beneath the landfill.

Hydraulic gradients beneath the upland are quite small, although they undoubtedly increase near the lowland to the north. The relatively deep water table and the complex nature of the glacial drift succession make it difficult to determine vertical components of flow. The permeable nature of the sand and gravel aquifer and the presence of less permeable till and shale below indicate that the lateral component of flow in the sand and gravel aquifer is probably dominant. This water probably discharges into the canal and river in the lowland to the north.

The hydraulic conductivity of soil samples representing the range of materials present beneath the site was determined in the laboratory with an air-pressure permeameter (Soiltest Model K-670) using a falling head test. The results (appendix 9) illustrate the complex hydrogeologic character of the materials. Values ranged from 2.0×10^{-3} cm/sec to 6.3×10^{-4} cm/sec for sand, 5.8×10^{-6} to 3.8×10^{-6} cm/sec for silt lenses, and 2.5×10^{-8} to 4.5×10^{-8} cm/sec for glacial till. The fine texture, and resultant low hydraulic conductivity, of the glacial till impedes vertical infiltration toward the water table and may produce temporary zones of perched ground water. Because the surface of the till slopes toward the north beneath the landfill, infiltration through the overlying sand may encounter the less permeable till and flow laterally toward the north.

From Darcy's equation $v = kI$ where:

v = apparent velocity (flux), L/T
k = hydraulic conductivity, L/T
I = hdraulic gradient, L/L

an apparent rate of ground-water flow in the sand and gravel beneath the site was estimated. The actual or effective velocity is described by Hantush (1964) as the apparent velocity divided by the effective porosity of the

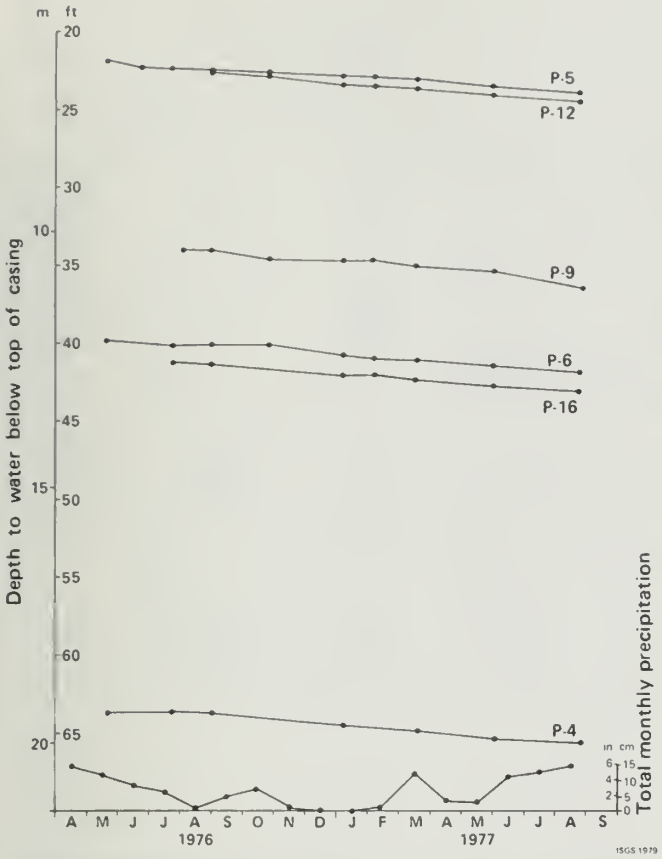


Figure 7. Water level changes in monitoring wells at the Geneseo landfill and precipitation at Geneseo, Illinois, from April 1976 to August 1977. Precipitation data from NOAA (1974-1977).

material. The effective porosity (n_e) is the portion of the pore space in a saturated material through which flow occurs, whereas the measurement of the percentage of voids in a porous medium yields a porosity (n) which is greater than n_e (Fried, 1975). This is explained by the occurrence of dead-end pores and water adsorbed to the solid matrix which does not contribute to the flow. Measurements of the total porosity of sands compiled by Davis (1969) range from about 34 to 41 percent. An effective porosity of 0.3 was estimated for the sand and gravel beneath the landfill. Based on this value, the effective (actual) velocity of ground water beneath the upland is approximately 7 feet/yr (2.1 m/yr); however, with the higher gradients near the lowland this may approach 137 feet/yr (42 m/yr).

The natural ground-water flow system beneath the landfill has probably been altered by pumpage from the municipal well field. The shallow wells and springs east of the landfill have diverted natural discharge by gravity into the adjacent reservoir; well E-3, finished in sand and gravel at a depth of 65 feet (20 m), is periodically pumped at a rate of 250 to 350 gallons per minute. Although this well is up-gradient from the landfill, pumping may have affected ground-water flow in ths sand and gravel beneath the landfill. It seems unlikely, though, that this caused the flow of leachate into well E-3 as the quality of water from the well has not appreciably changed since it was installed (Johnson and Cartwright, 1977). The relatively thick, impermeable layer of glacial till which slopes toward the north beneath the site appears to have controlled the migration of leachate from the landfill. The chemical analyses of soil, soil moisture, and ground water (to be discussed later) confirm that migration of leachate has occurred but that ground water beneath the site is virtually unaffected.

LYSIMETER INSTALLATION AND SAMPLING RESULTS

At the Geneseo landfill, eleven lysimeters were installed in five borings. Six lysimeters were installed beneath refuse emplaced approximately in 1970. The other lysimeters were installed in borings beneath older portions of the site that had been used for indiscriminate dumping in the early 1900s. The background quality of soil moisture was also determined in areas not affected by waste disposal. The average volume of each of the 56 samples obtained from the lysimeters was 316 mL. Descriptions of lysimeter installation at Geneseo are included in appendix 2.

WATER QUALITY

Ground water

The results of the chemical analyses of samples of ground water from monitoring wells adjacent to the Geneseo landfill are presented in appendix 4. There has also been long-term monitoring (since 1909) of the springs and wells used for public water supply.

Data show little evidence of contamination of groundwater by leachate. Shallow ground water from two wells (P-6 and P-12), however, had appreciably higher levels of COD, chloride, and sodium. Located immediately north and northeast of the landfill, respectively, these two wells appear to have been affected by leachate contamination. Water from well P-6 usually had a slight leachate odor; water from P-12 was clear and did not appear to be contaminated upon first examination. The highest levels of COD, however, were found in P-12.

As a result of the indiscriminate refuse disposal in the first half of the century, ground water in a large area surrounding the landfill may have been partially contaminated; however, the low chloride concentrations and the generally consistent, relatively-low TDS content of ground water beneath the site indicate little, if any, contamination by leachate.

Elevated concentrations of sulfate in water from the city wells finished in the underlying sand and gravel aquifer have been associated (Walker 1969) with the landfill.

TABLE 2. Range of composition of soil-moisture samples from lysimeters at the Geneseo landfill.

Parameter	Uncontaminated				Contaminated			
	Minimum		Maximum		Minimum		Maximum	
	(mg/L)[a]	(meq/L)[b]	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Ca	53	2.64	83	4.14	64	3.10	3,760	187.62
Fe	0.6	0.02	1.5	0.05	6.1	0.22	240	8.59
Hg	<0.2	-	<0.2	-	<0.2	-	<0.2	-
K	0.4	0.01	1.5	0.04	0.7	0.02	17.0	0.43
Mg	18.4	1.51	18.8	1.55	7.0	0.58	120	9.87
Na	18	0.78	36	1.57	160	6.96	1,260	54.81
Pb	<0.01	-	<0.01	-	<0.01	-	<0.01	-
Zn	0.01	0.001	0.06	0.002	0.01	0.001	0.17	0.005
Alk ($CaCO_3$)[c]	210	3.44	330	5.41	830	13.60	9,410	154.23
Cl	31	0.87	93	2.62	110	3.10	3,583	101.08
COD	6	-	14	-	22	-	8,898	-
NH_4-N	0.0	-	0.0	-	0.0	-	11	0.61
NO_3-N	0.2	0.003	0.3	0.005	<0.1	0.0	6.8	0.11
pH[c]	6.05	-	6.72	-	6.48	-	7.05	-
SC[c]	525	-	775	-	1090	-	7,000	-
SO_4	35	0.73	178	3.71	<0.01	0.00	<0.01	0.00
TDS	537	-	700	-	930	-	10,186	-

[a] Except Hg (ppb), pH, and SC (μmhos).
[b] Milliequivalents per liter.
[c] Field measurement.

Sulfate was present in appreciable amounts in water from nearly every shallow well in this area, however, and was not accompanied by the high concentrations of other constituents usually associated with contamination by leachate. Not surprisingly, the lowest concentrations of sulfate occurred in well P-6 where contamination produced reducing conditions. Samples of contaminated soil moisture contained no measurable sulfate, and no detectable sulfide odors were present in either ground water or soil moisture sampled beneath the site. The onset of reducing conditions resulting from refuse decomposition has been associated with concentrations of sulfate near some landfills (Kunkle and Shade, 1976); however, there have been no other indicators of contamination by leachate. A source for the high sulfate concentrations was not found; however, ground water associated with Pennsylvanian shale in Illinois is frequently mineralized, containing high levels of sulfate and chloride.

Soil moisture

A total of 54 water samples were submitted for chemical analysis from lysimeters at the Geneseo landfill between July 23, 1976, and August 25, 1977. The results of the analyses are presented in appendix 5. The range in quality of uncontaminated and contaminated soil moisture is shown in table 2 in absolute (mg/L) and relative (meq/L) concentrations. The order of maximum relative concentrations in contaminated soil moisture was in general: Ca> Alkalinity> Cl> Na> Mg> Fe. The pH of contaminated soil moisture ranged from 6.48 to 7.05. Uncontaminated soil moisture had minimum relative concentrations in the decreasing order: Alkalinity> Ca> Mg> Cl> Na> SO_4 and pH ranging from 6.05 to 6.72. The actual order of concentrations in individual samples of contaminated soil moisture varied slightly depending on the character of the refuse.

The long history of waste disposal is reflected in the quality of soil moisture collected from different locations beneath the site. The quality of water from the six lysimeters installed beneath the refuse (S-1 and S-3) reflects the impact of refuse disposal in trenches from 1967 to 1975. Other lysimeters installed beneath older portions of the site (S-7, 8, and 10) appear to show the long-term effects of waste disposal as well as the quality of modern infiltration. Except for leachate samples from the refuse at the Crystal Lake landfill, soil moisture from S-1 and S-3 at Geneseo was generally more contaminated than that from any other site.

Effect of depth below refuse on soil-moisture quality. Plots showing the concentrations of selected parameters in soil moisture and ground water versus depth below the refuse (as used by Apgar and Langmuir, 1971) are presented in figure 8. A generalized cross-sectional profile of the landfill is included in each diagram. The hachured line indicates the maximum concentration of the parameter at that particular depth. The concentration of each parameter, except calcium and specific conductivity, is plotted on a logarithmic scale.

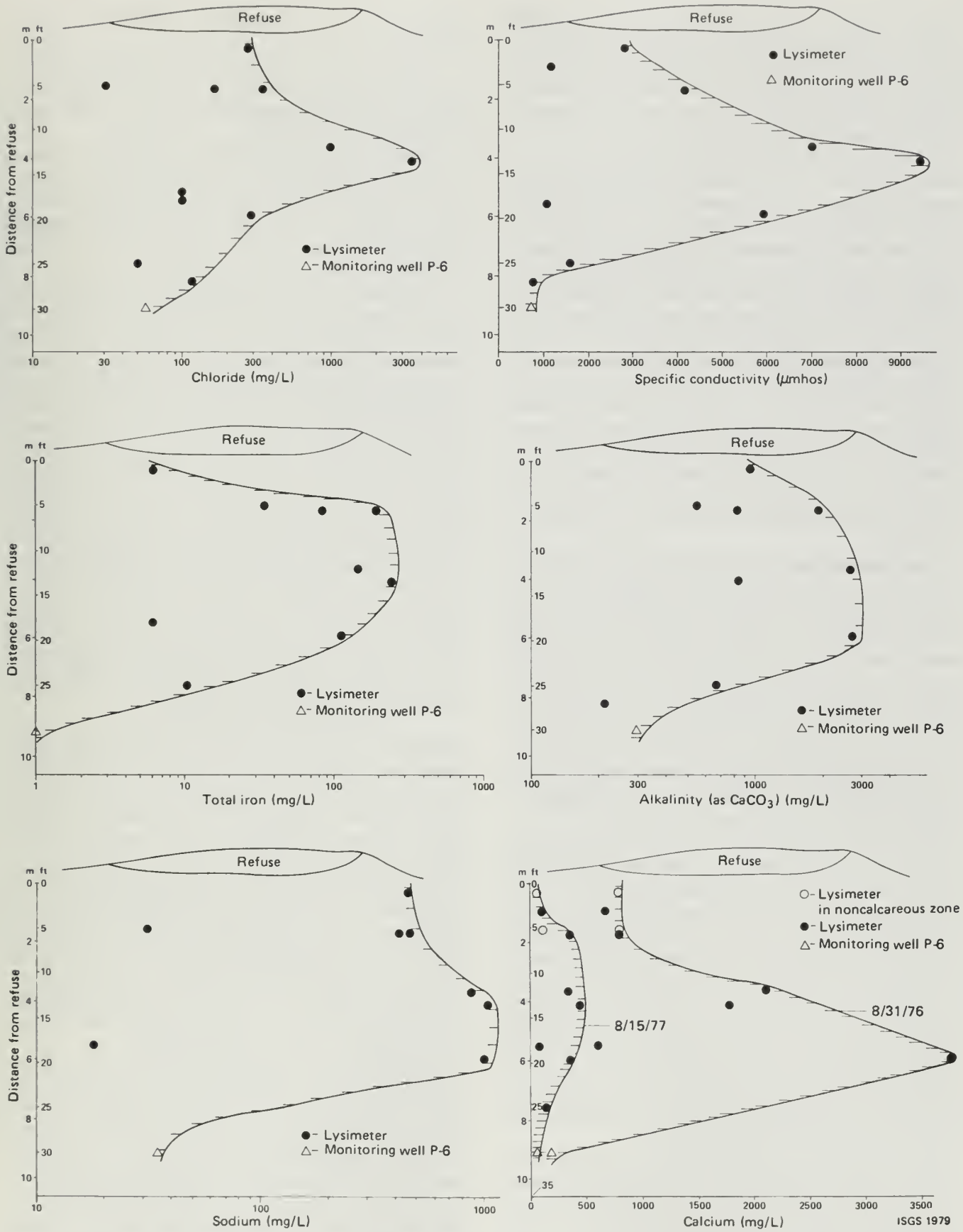


Figure 8. Concentrations of selected parameters as a function of depth below refuse in water beneath the Geneseo landfill on August 25, 1977. The hachured line represents the maximum concentration observed at that particular depth. Calcium concentration in water on August 31, 1976 and August 25, 1977.

The range in values with depth in these diagrams primarily indicates the variation of soil-moisture composition in respect to distance from the refuse emplaced from 1967 to 1975. The samples with the highest concentrations of each contaminant were generally from the lysimeters beneath the refuse in S-1 and S-3.

The effect of increased depth below the refuse on several parameters, such as specific conductivity and iron content, illustrates two processes that have apparently controlled the extent of contamination: (1) the attenuation of leachate in the unsaturated zone, and (2) an apparent decrease in the concentrations of constituents released by the refuse, possibly, for the last several years. The concentration profiles of chloride and specific conductivity (fig. 8) in soil moisture with depth below the refuse are similar; the conductivity profile appears more pronounced because it is plotted on a linear rather than a logarithmic scale. The chloride and conductivity maxima were both situated approximately 15 feet (4.5 m) below the refuse. The higher levels of chloride, conductivity, and other parameters in monitoring well P-6 probably indicate limited, shallow ground-water contamination. Well P-6 is situated beneath 15 feet (4.5 m) of refuse at the extreme northern edge of the landfill.

The concentrations of chloride and total ionic species (as conductivity) decreased toward the refuse from maxima at 15 feet (4.5 m). Chloride concentrations remained relatively constant to a depth of 6.5 feet (2 m) below the refuse. These data indicate that chloride concentrations recently released by the refuse have been fairly constant. It appears that leachate has migrated at an average rate of 3 feet/year (1 m/yr) since 1967. The actual rate of migration has probably been greater because much of the refuse was not emplaced until later (from 1971 to 1975), and the succession of materials beneath the site has resulted in highly variable rates of soil-moisture movement.

Much of the apparent attenuation occurring beneath the site is due to the succession of geologic materials. The permeable sands immediately beneath the refuse allow relatively rapid migration of contaminated soil moisture; the limited attenuation that does occur in the sand is mainly due to more oxidizing conditions and the presence of occasional lenses of silt and silty clay. At a depth of approximately 27 feet (8 m), however, fine-grained, relatively impermeable till serves as both a physical and geochemical barrier to leachate migration. Thus, the great degree of attenuation of most parameters below a depth of 27 feet (8 m) has probably been caused by the layer of till. Actual rates of leachate migration cannot accurately be determined with the limited data available.

The distribution of total iron with depth (fig. 8) is similar to that of chloride and conductivity. Maximum levels of iron at depths of 6.6 to 16 feet (2 to 5 m) reflect the more anaerobic conditions indicated by low Eh values in that interval. The rapid decrease in iron below a depth of 25 feet (8 m) probably reflects the removal of large quantities of iron by precipitation and cation exchange reactions.

The distribution of alkalinity (as bicarbonate) (fig. 8) may reflect the long term contribution of organic acids and CO_2 from the wastes following the removal of more readily leached inorganic constituents.

Sodium concentrations in figure 8 reflect persistent, moderately high sodium production that was due to continued leaching of the refuse. Levels of sodium appear to have stabilized at 400 to 500 mg/L immediately beneath the refuse; maximum values of 100 mg/L are present from 13 to 26 feet (4 to 8 m) below the refuse.

The calcium concentrations of soil moisture are directly related to ion-exchange reactions of leachate with the soil. The influence of soil chemistry on calcium and magnesium concentrations in soil moisture is discussed later. The interaction of highly contaminated leachate and calcareous soils results in the release of calcium and magnesium from exchange sites on clays, as noted by Griffin et al. (1976). This action produces calcium concentrations much greater than those initially leached from the refuse. Figure 8 shows the calcium concentrations in water beneath the refuse on two occasions, August 31, 1976, and August 25, 1977. Extremely high concentrations of calcium were present in calcareous materials below the landfill on August 31, 1976. Soil moisture from the noncalcareous leached zone beneath the refuse contained levels of calcium apparently derived only from leaching of the overlying refuse. A large decrease in calcium concentrations shown in the distribution one year later, reflects a decline in the release of calcium from ion exchange sites.

Variation in quality of soil moisture with time and depth below refuse. Water samples were collected from lysimeters at Geneseo at intervals ranging from 2 to 270 days from July 23, 1976, to August 25, 1977. Because of the long history of waste disposal at the site, a comparison of the initial and long-term effects of waste disposal was not possible. The relatively detailed sampling during the study period, covering essentially one year, illustrated the relative differences in the quality of soil moisture with time and depth quite accurately. The changes with time in the concentrations of selected parameters in soil moisture are presented in figure 9. The diagrams also illustrate the character and variation in the quality of soil moisture beneath different portions of the landfill site.

Concentrations of most parameters remained fairly steady with time. Fluctuations that did occur appear to have resulted from variable infiltration. Samples from the lysimeters indicated the continued leaching of inorganic substances from overlying materials. Even soil-moisture samples that appeared to be uncontaminated often contained elevated concentratons of parameters such as iron and calcium; possibly this indicates the widespread effects of waste disposal.

A plot of total dissolved solids (TDS) with time

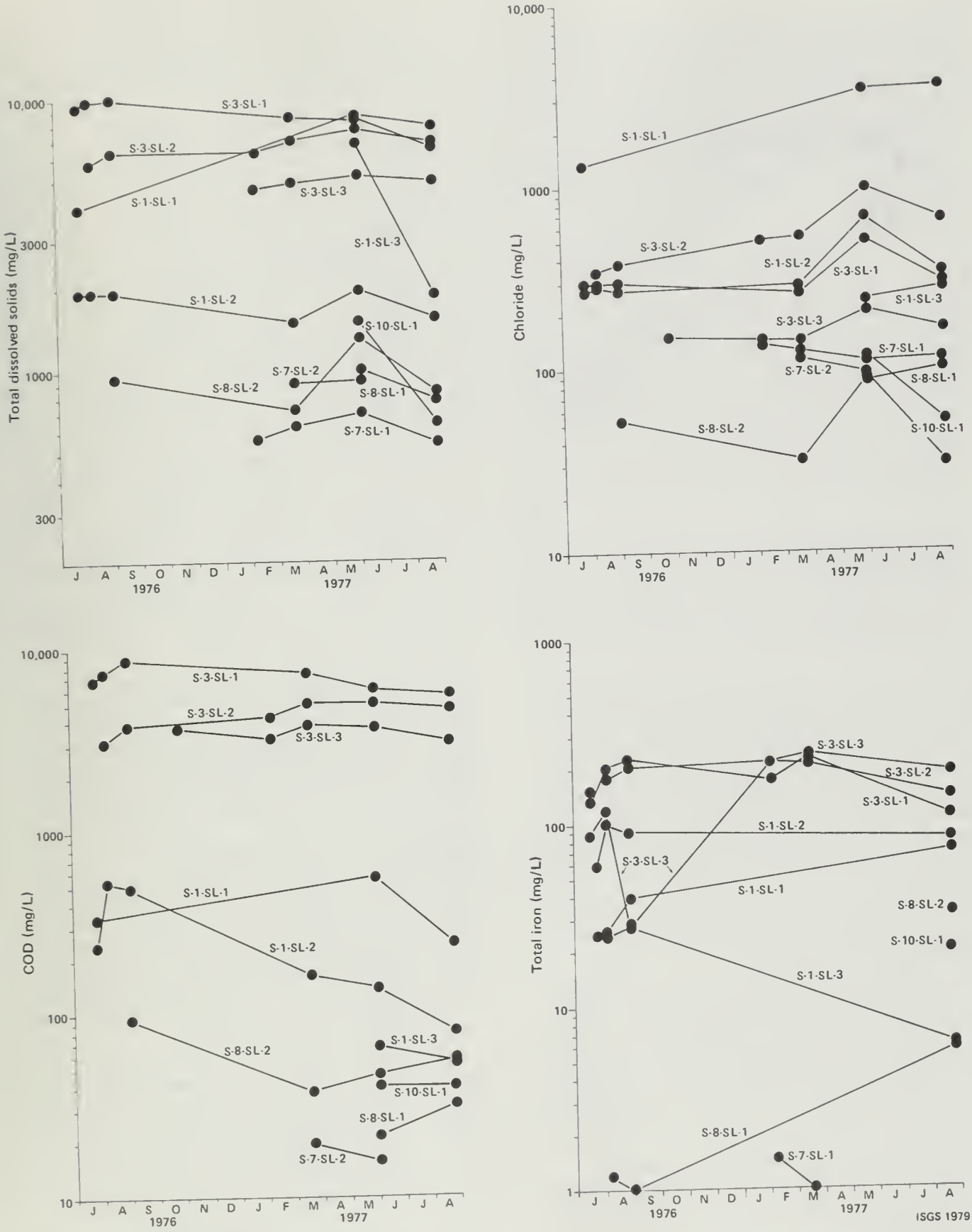


Figure 9. Changes in concentrations of selected parameters with time in soil moisture from lysimeters beneath the Geneseo landfill. S-3-SL-1 represents suction lysimeter number 1 in boring S-3.

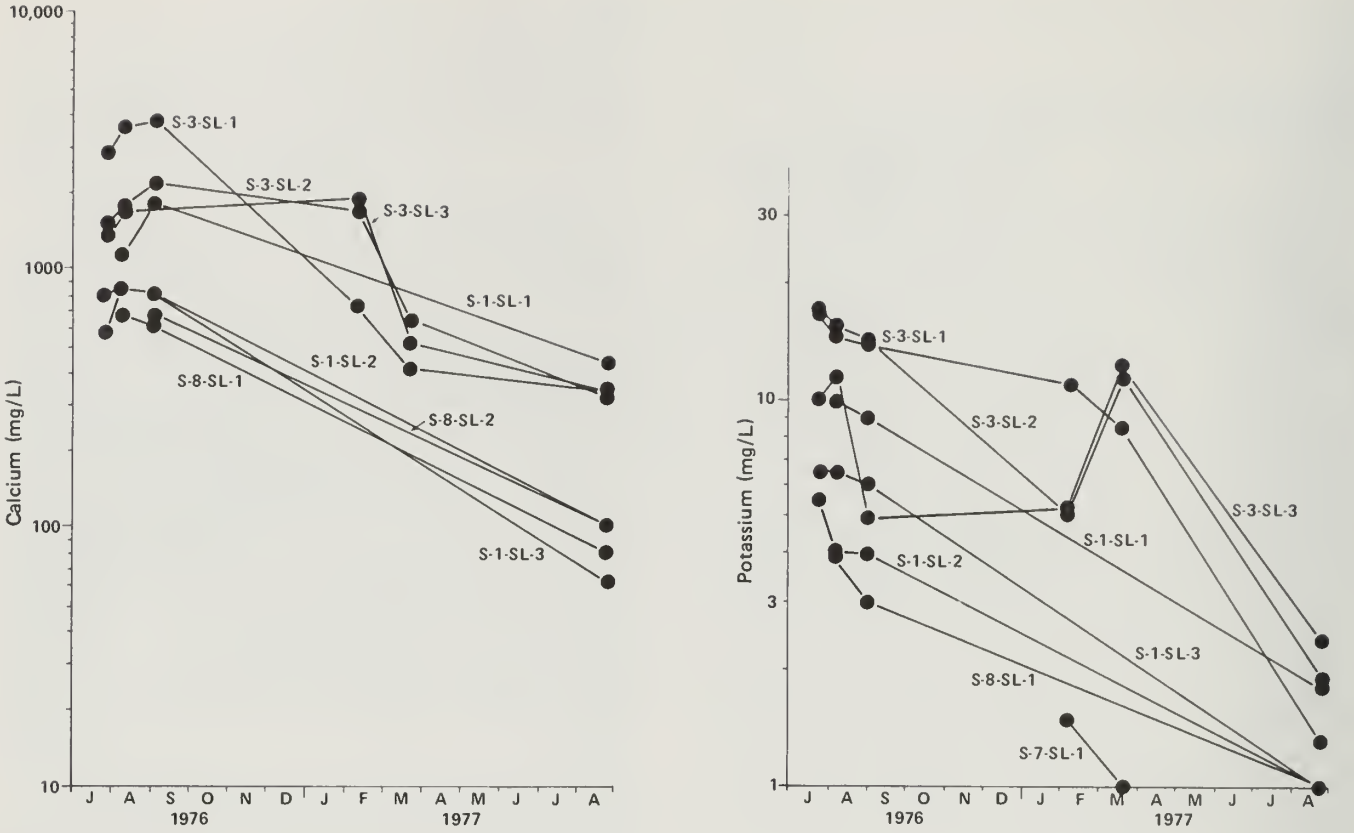


Figure 9. *(continued)*

ISGS 1979

illustrates a general increase with depth to about 17 feet (5 m) in S-1 and S-3, but the relative concentrations remained fairly stable. Some lysimeters showed an increase in TDS from March to June 1977; this probably can be associated with increased infiltration. Chloride concentrations (fig. 9) showed a similar trend; however, it should be noted that those lysimeters showing the greatest concentrations of chloride did not necessarily show the highest levels of TDS. Lysimeters S-1-SL-1 and S-3-SL-2, placed at approximately the same depth below the refuse, reflected the chloride maximum recorded at that depth (fig. 8) for samples collected August 25, 1977. Chloride concentrations also increased in June 1977, except in the deeper lysimeters of S-7 and S-8.

While chloride concentrations were consistently higher in S-1-SL-1 and S-3-SL-2 than in other lysimeters, concentrations of COD in S-3 were much greater than in S-1. The relatively constant levels of COD in S-3 must reflect the age and character of the refuse in the vicinity. Decreases in COD with time in S-1-SL-2 were associated with increases in COD in the deeper lysimeter (S-1-SL-1); possibly this may indicate the downward migration of leachate.

Total iron concentrations (fig. 9) exhibited marked fluctuations with time. Samples from lysimeters in boring S-3 contained consistently more iron than those from other borings. Concentrations of iron in S-3 decreased slightly with depth.

Calcium and potassium concentrations in soil moisture exhibited a general decline during the study. The reduction in calcium concentrations may have been due to the continued loss of Ca from exchange sites (fig. 9) in response to leachate-soil interaction. The reason for the general reduction in potassium concentrations after March 1977 is unknown.

No lead or mercury was detected in any of the soil moisture samples, and concentrations of zinc apparently did not indicate contamination. Concentrations of sulfate in contaminated soil moisture were essentially zero. In relatively uncontaminated soil moisture, concentrations of sulfate reached 178 mg/L in S-7-SL-2; this indicates a near surface source of soluble sulfur compounds. Whether this accounts for the high concentrations of sulfate in the municipal wells such as E-3 is unknown.

Soil-moisture samples from Geneseo indicated the expected effects of waste disposal in a permeable medium. Maximum concentrations of most parameters were present at depths of 16 to 20 feet (5 to 6 m) below the refuse. Below that depth, however, significant attenuation appears to have been caused by a layer of fine-grained glacial till that has restricted vertical migration and has provided increased ion-exchange capacity. The net effect has been a reduction in the degree of contamination, such that soil moisture and ground water at depths of 26 to 30 feet (8 to 9 m) had chloride concentrations only 2 percent of

TABLE 3. Composition of soil moisture and ground water at the Geneseo landfill.

	Leachate—soil moisture (mg/L)[a]	Uncontaminated soil moisture (mg/L)	Ground water (mg/L)
Ca	3,760	53	54
Fe	240	0.6	0.8
Hg	<.2 ppb	<.2 ppb	<.2 ppb
K	17	0.4	1.7
Mg	120	18	59
Na	1,260	18	31
Pb	<.01	<.01	<.01
Zn	0.17	0.01	0.06
Alk ($CaCO_3$)[b]	9,410	210	352
Cl	3,583	31	56
COD	8,898	6	457
NH_4-N	11	0.0	
NO_3-N	7	0.2	1.5
pH[b]	7.05	6.05	7.70
SC[b]	7,000	525	750
SO_4	<.01	35	12
TDS	10,186	537	480

[a]Except Hg (ppb), pH, and SC (μmhos).
[b]Field measurement.

the maximum observed concentrations. Similar reductions occurred for iron, sodium, and other parameters. A significant amount of contaminated soil moisture probably flows laterally at the contact of the sand with the underlying glacial till, eventually entering the ground-water system in the lowland to the north. No deterioration in water quality was observed in surface water or shallow ground water in the lowland north of the site, however.

SUMMARY

The typical composition of both contaminated and uncontaminated soil moisture and of ground water at the Geneseo landfill is shown in table 3. Although the composition of ground water and uncontaminated soil moisture beneath the site is very similar, the composition of leachate-contaminated soil moisture is quite different. Except for heavy metals, leachate-soil moisture is generally highly contaminated, predominantly by chloride, alkalinity, sodium, magnesium, iron, COD, and, frequently, by calcium.

The relative distribution of major cations in groundwater and soil moisture samples from Geneseo is illustrated in figure 10. The general composition of uncontaminated soil moisture differs slightly from that of ground water; however, the composition of leachate, represented only by

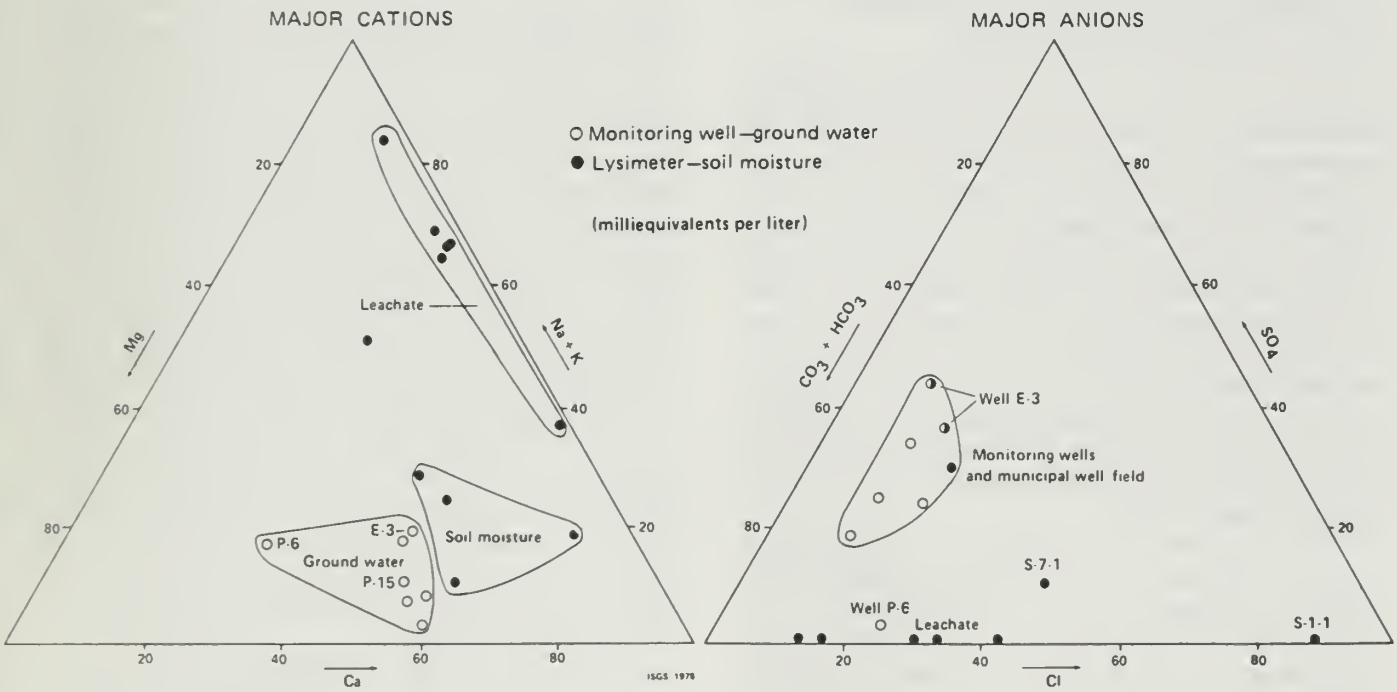


Figure 10. Distribution of major cations and anions in soil moisture and ground water at the Geneseo landfill. Results are in milliequivalents per liter.

samples of soil moisture is vastly different. Soil moisture contaminated by leachate contains a much greater relative percentage of sodium plus potassium and much less magnesium and calcium. Although the analysis of ground water from well P-6 indicates possible contamination, the distribution of major cations in P-6 is similar to that in ground water from unaffected wells. Wells E-3 and P-15, both finished in the sand and gravel aquifer underlying the landfill, show no indication of contamination by leachate. Previously, the high concentrations of sulfate in well E-3 have been thought to result from pollution of ground water beneath the landfill.

The relative distribution of major anions in ground water and soil moisture is also shown in figure 10. Samples affected by leachate are quite distinct in composition from those samples of uncontaminated ground water and soil moisture. Although ground water in the area frequently contains appreciable concentrations of sulfate, contaminated soil moisture and ground water from well P-6 contain virtually no sulfate.

SOIL CHEMISTRY

Attenuation of leachate is strongly affected by ion-exchange processes that are a function of the quantity and mineralogy of clay minerals in the surrounding materials. Geologic materials beneath the Geneseo landfill range from well-sorted sand and gravel to silty-clay glacial till. The clay content (< .0039 mm) of these materials varies from 1 to 75 percent. Table 1 illustrates the average texture, clay mineralogy, and range of cation exchange capacity (CEC) for each unit present beneath the landfill.

The highest CEC values at Geneseo were associated with thin, interbedded lenses of silt and the underlying glacial till of silty clay. The thick deposits of fine- to medium-grained sand immediately beneath the landfill have the lowest CEC values and percentages of clay. As expected, the relatively coarse-textured materials having low CEC result in limited attenuation of leachate in the unsaturated sands beneath the landfill. Lenses of silty sand, sandy silt, and silt, which have slightly greater clay contents and CEC, are generally too thin and discontinuous to provide substantial attenuative capacity. The glacial till beneath the entire site appears to represent a significant barrier to leachate migration. Its fine-grained texture and higher CEC both retard and reduce the effects of leachate migration beneath the site.

The effectiveness of cation-exchange processes depends on the chemical character of the leachate and the exchange capacity of the medium. Table 2 illustrates the range of concentration of both uncontaminated and contaminated soil moisture from lysimeters at the Geneseo landfill. Both absolute (mg/L) and relative (meq/L) concentrations are indicated for most parameters.

Chemical analyses were made of 20 soil samples from borings beneath and adjacent to the landfill at depths of 7 to 38 feet (2.1 to 11.6 m). The results represent total concentrations and are included in appendix 3. Cation exchange capacity data for materials beneath the site (table 1) ranged from 0.6 to 10.1 meq/100 g of soil. There were few apparent differences between samples of contaminated and uncontaminated soil.

The depth of carbonate leaching varied from approximately 12 feet (3.7 m) to 30 feet (9.1 m). This is reflected by the Ca and Mg content of soil samples. Samples from boring S-1 were noncalcareous to a depth of 30 feet (9.1 m) where calcareous till was encountered. Total Ca concentrations ranged from 0.18 to 0.56 percent in noncalcareous sands and silts, to 0.90 percent in the upper part of the till in S-1. The underlying calcareous till, on the other hand, contained 3.11 percent Ca. Concentrations of Mg were very similar, varying from 0.07 to 0.42 percent in the sand and silt deposits, to 0.62 percent in noncalcareous till, whereas the calcareous till below had 2.49 percent Mg. The Ca content of calcareous soil samples from the Geneseo landfill ranged from 2.61 to 6.17 percent and the Mg content varied from 1.00 to 3.84 percent.

The relative absence of Ca and Mg from noncalcareous soils beneath the landfill affects the cation exchange capability of the materials and, as a result, the quality of soil moisture beneath the site. Generally, clay minerals in these soils are originally Ca-saturated. The large number of competing cations in highly contaminated leachate are preferentially adsorbed on exchange sites and cause the release of Ca and Mg from the exchange sites (Griffin et al., 1976); this is the "hardness-halo" frequently observed in the vicinity of landfill sites where concentrations of Ca and Mg in ground water are much greater than in the original leachate. Soil samples from boring S-3 were calcareous at a depth of 14 feet (4.3 m). Soil-moisture samples from lysimeters in S-3 at depths of 18 to 32 feet (5.5 to 9.8 m) had Ca concentrations of 350 to 3760 mg/L and Mg concentrations of 20 to 120 mg/L. Soil-moisture samples from two lysimeters in noncalcareous materials in S-1 at depths of 18 and 22 feet (5.5 and 6.7 m), however, had much lower Ca (64 to 840 mg/L) and Mg concentrations (10 mg/L). Samples from the deepest lysimeter (S-1-SL-1), in calcareous material at 30 feet (9.1 m), had concentrations of Ca and Mg up to 1,800 and 71 mg/L respectively.

Chloride concentrations provide the only apparent evidence of contamination of soil samples by leachate. Background concentrations of chloride were approximately .02 percent; however, concentrations in S-1 of .18 to .21 percent were present at the contact of the sand and the underlying glacial till, approximately 12 to 13 feet (3.7 to 4.0 m) below the refuse.

Total concentrations of lead were below the limit of detection (15 ppm), and sulfate was absent in each sample. Mercury was detected in soil samples below the landfill

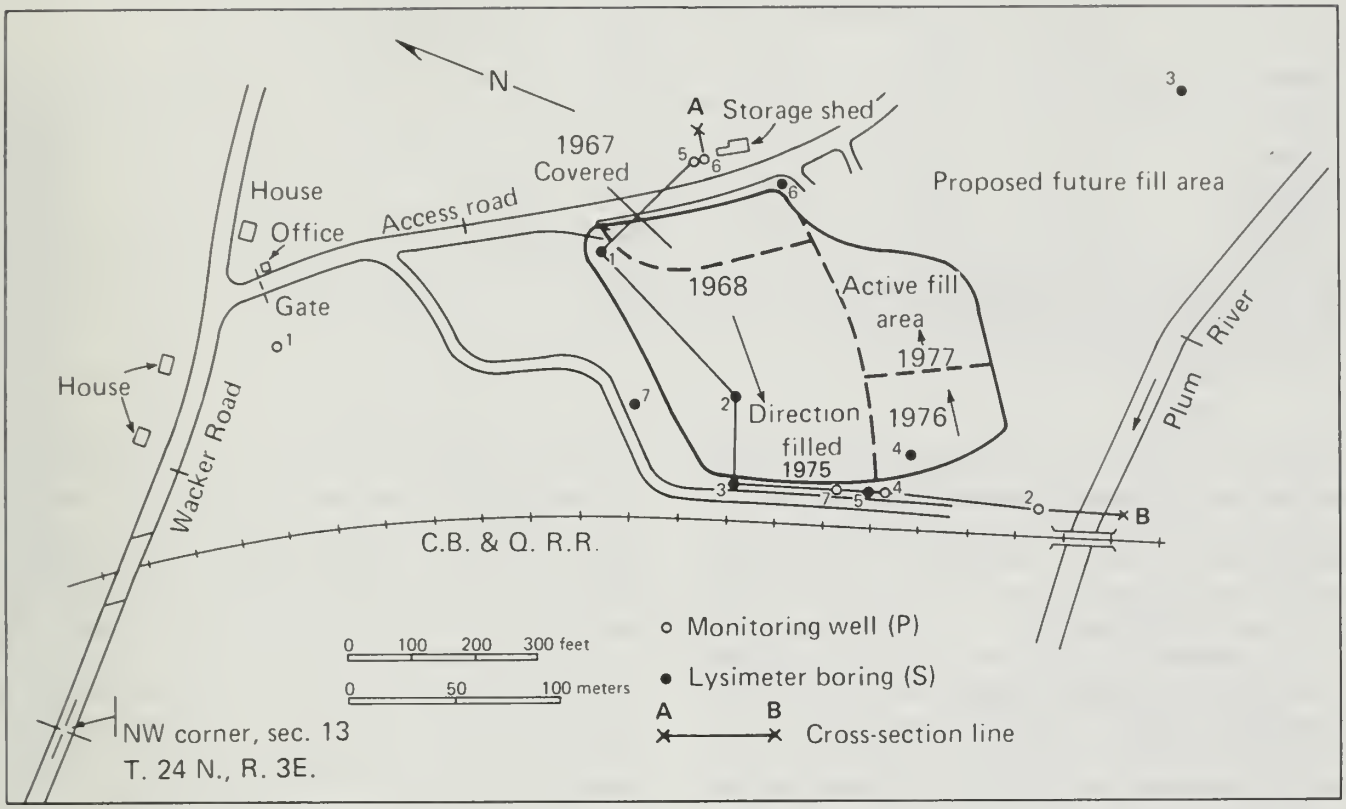


Figure 11. Map of Savanna landfill showing the general sequence of filling and the locations of monitoring wells, lysimeter borings, and the Plum River.

at levels of 0.02 to 0.10 ppm; however, these appear to represent background concentrations. Concentrations of zinc generally increased with clay content from approximately 7 to 10 ppm in sand, to over 60 ppm in silty clay till; however, no patterns of contamination were observed. Adsorption on iron oxides may be responsible for increases in zinc concentration.

Elevated concentrations of iron and potassium were also associated with the presence of fine-grained material and appeared to increase with depth in borings S-1 and P-4. Iron concentrations ranged from 0.63 percent in sand 6 feet (1.8 m) beneath the refuse, to 3.13 percent in uncontaminated silty clay till at a depth of 14 feet (4.3 m) below the refuse. Potassium ranged from 0.96 percent in sand to 3.17 percent in fine-grained till beneath the refuse.

Sodium concentrations were also low (0.51 percent) in sand immediately beneath the refuse; however, the greatest concentration observed at the site, (1.11 percent), was in silty sand 11 feet (3.4 m) beneath the refuse in S-1. The underlying glacial till contained only 0.40 percent sodium, similar to that of uncontaminated samples of till from P-5. The increase in sodium beneath the refuse in S-1 may represent the adsorption of sodium from leachate by noncalcareous material.

SAVANNA MUNICIPAL LANDFILL

DESCRIPTION OF SITE

The Savanna municipal landfill is in Carroll County in northwestern Illinois in the NW ¼ Sec. 13, T. 24 N., R. 3 E. (fig. 1). The site consists of approximately 23 acres (9.3 ha) adjacent to the Plum River in the Mississippi River lowland. The site is bounded by Wacker Road on the north, the Chicago, Milwaukee, St. Paul, and Pacific Railroad on the west, and by the Plum River, which flows toward the Mississippi River around the eastern and southern edges of the site area. Figure 11 is a general map of the landfill site showing the locations of monitoring wells and lysimeter borings. The elevation of the land surface is approximately 600 feet (183 m) above sea level. The surrounding area is characterized by low swampy land and sandy terraces of the Mississippi River floodplain.

The Savanna landfill is in an abandoned sand pit that was excavated to a depth of approximately 25 feet (7.6 m) prior to the emplacement of refuse. Fine- to coarse-grained sand from the excavation has been used for daily cover material. Disposal of refuse began in 1967 with

TABLE 4. Mean texture, clay mineralogy, and range of cation exchange capacity (CEC) of materials beneath the Savanna landfill.

Material	Texture[a]				Clay mineralogy[b]			CEC[c]
	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Ex (%)	I (%)	C + K (%)	
Sand	2	92	5	3	-	-	-	1.1-2.3
Silty sand	0	53	31	16	65	23	12	8.1-23.0
Sandy silt	0	22	63	15	63	22	15	8.5
Pebbly sand	15	95	3	2	-	-	-	-
Clayey silt	0	10	66	24	-	-	-	10.7

[a]Gravel, 2 mm; sand, 2 to 0.0625 mm; silt, 0.0625 to .0039 mm; clay, .0039 mm.
[b]Ex = expandables, I = illite, C + K = chlorite plus kaolinite.
[c]Milliequivalents per 100 g dry soil.

the filling of an abandoned sand pit in the northern part of the site and progressed in a southwesterly direction. According to the operator, refuse was placed in two lifts, totalling approximately 25 feet (7.6 m) in the northern half of the site, eventually rising about 15 feet (4.6 m) above the original land surface.

The majority of the fill material consists of general household refuse from the Savanna area as well as some miscellaneous organic material and construction debris. The base of the site was reportedly not prepared or lined prior to the emplacement of refuse. Filling was completed in the northern portion of the site in 1975, and the sand pit immediately to the south was excavated to accomodate additional refuse. Filling has continued in this area to the present. Some fine-grained, silty topsoil from an area adjacent to the site has been used on the northern portion of the landfill for final cover.

Weeds cover much of the northern portion of the landfill. The upper surface of the fill is relatively flat; however, the sides, especially the west side, are very steep, and the loose, sandy cover material is eroded. Refuse is locally exposed along the steep sides of the fill, and leachate springs were observed along the southern edge of the northern half of the site (the operating face) and occasionally at the northwestern corner of the fill.

Salvageable material, including old machinery and iron pipe, is stored at the site along the eastern edge of the landfill. Stockpiles of salt for road use in the winter are also stored uncovered in this area. Deposits of salt are visible on the ground surface in the vicinity of the salt piles; rainfall has eroded, dissolved, and deposited some of the salt on the surface upon infiltration. The implications of this are discussed in later sections.

GEOLOGY

The Savanna landfill is situated on a low terrace adjacent to the Plum River in the Mississippi River floodplain. The site is underlain primarily by alluvial sand and silt deposits ranging from 28 feet (8.5 m) thick in the east to more than 60 feet (18.3 m) in the western portion of the site. The alluvial materials, although generally uniform medium- to coarse-textured sand or sand and gravel, contain occasional thin lenses of silt and silty clay. Some surficial sand has been reworked by the wind into small dunes. The alluvium may also be underlain by deposits of glacial outwash silt or sand and gravel. The underlying bedrock consists of Ordovician dolomitic limestone of the Galena and Platteville Groups. The bedrock surface slopes toward the west beneath the site.

Descriptions of the borings made during this study are included in appendix 7; laboratory data from selected borings are presented in appendix 8. Table 4 summarizes the data on textures, minerals, and cation exchange capacity for each unit. A brief description of each stratigraphic unit follows:

Quaternary System
Pleistocene Series
Holocene Stage
Cahokia Alluvium (28 to 65 feet [8.5 to 20 m] thick)

Interbedded deposits of sand, silty sand, silt, and silty clay. Predominantly well-sorted, medium- to coarse-grained sand, grading to sand and gravel at depths of 20 to 30 feet (6 to 9 m) and becoming finer grained at depths below 40 feet (12 m). Calcareous except at the surface. The upper portion may have been partially reworked by the wind. Upper surface locally contains poorly developed Modern Soil, but most of the site has been disturbed by mining activities.

Wisconsinan Stage
Outwash deposits (0 to 20 feet [0 to 6 m] thick)

Water-laid deposits of calcareous sand and gravel, silt, and clay. Overlying alluvium may include some reworked Wisconsinan materials; the outwash probably thickens to the west in the buried bedrock valley.

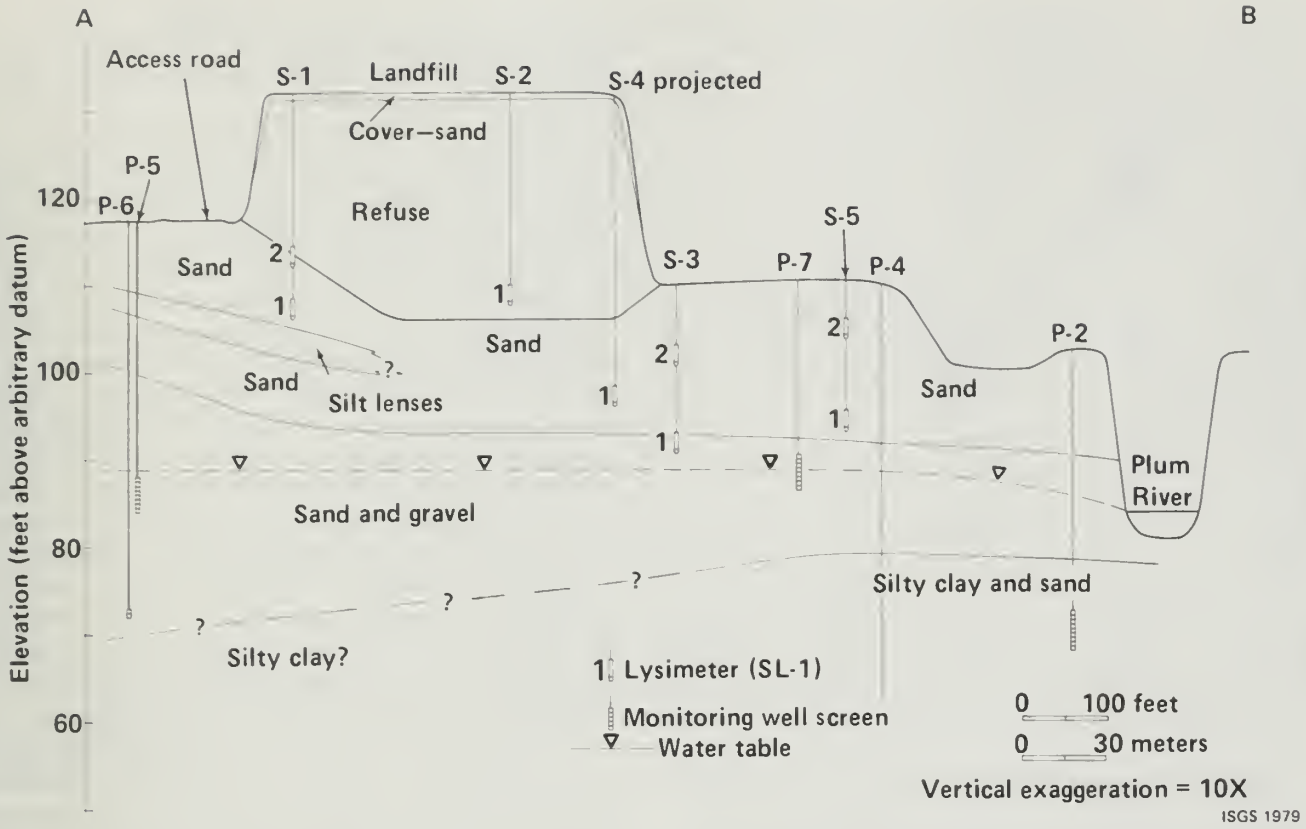


Figure 12. Cross section A-B through the Savanna landfill site showing a portion of the monitoring well-lysimeter network and the general geologic sequence.

Ordovician System
Galena and Platteville Groups

Bedrock consisting of dolomite and dolomitic limestone, coarsely crystalline and locally well fractured.

The Modern Soil is the only soil type recognized in the geologic succession at this site. It is present at the surface only on those portions of the site that have not been excavated. Where present, the Modern Soil has been mapped by the USDA Soil Conservation Service (Ray, Rehner, and Fehrenbacher, 1975) as consisting primarily of the Lamont Series; light-colored, well-drained soils developed from wind- and water-deposited loose sand under forest vegetation. Lamont soils are described as having moderately rapid permeability and low available water capacity. The glacial drift is generally leached to a depth of 7 feet (2 m).

HYDROGEOLOGY

Figure 12 is a cross section of the landfill and underlying materials showing a portion of the network of lysimeters and monitoring wells at the site. In addition to the three pre-existing observation wells adjacent to the landfill (fig. 11), four monitoring wells were installed during this study. Installation data for each well are included in appendix 1.

Water levels in the monitoring wells varied from approximately 10 to 13 feet (3 to 4 m) below the base of the refuse. Figure 13 shows the changes in static water levels and the average monthly precipitation during the study. The decline in water levels from April 1976 to February 1977 was associated with greatly reduced precipitation during the period. Water levels rose rapidly following increased precipitation and snowmelt during and after March 1977. It is interesting to note that water levels in 4 wells (P-1, 5, 6, 7) varied in a very similar manner, whereas those in P-2 and P-4 reacted quite differently. Wells P-1, 5, 6, and 7 are situated in the northern portion of the site (fig. 11) at higher elevations than the Plum River and wetlands to the east and south. Well P-4 in the southwest portion of the site, on the other hand, is relatively deep (50 feet [15.2 m]) and is finished in a sequence of silty clay and sand deposits; it might reflect water level changes in a semiconfined aquifer during the period of increased recharge.

The data on water levels indicate that shallow groundwater flow is in a southwesterly direction beneath the landfill, ultimately discharging into the Plum River. Gradients beneath the upland area of the site are almost negligible. Gradients in the southwestern portion of the site are, in

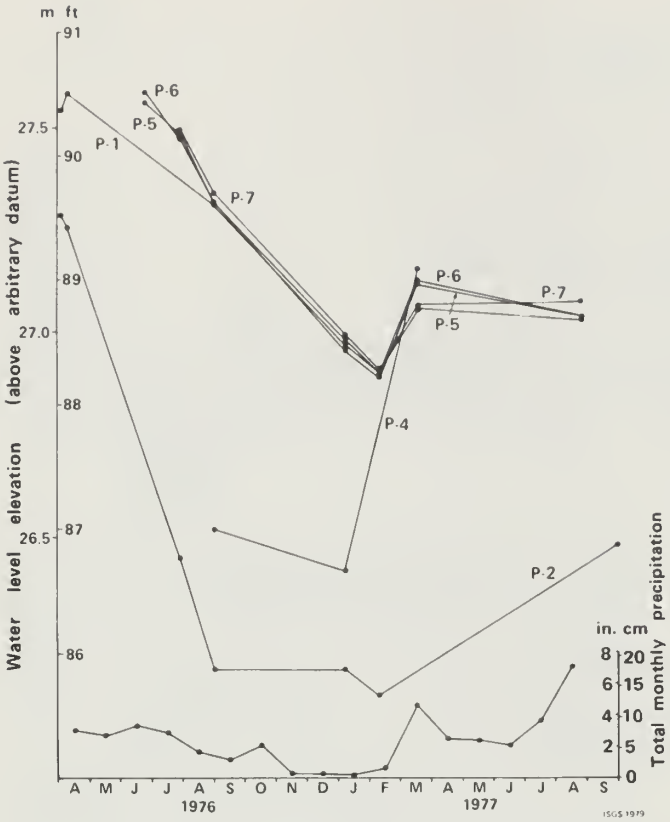


Figure 13. Water level changes in monitoring wells at the Savanna landfill and precipitation at Fulton, Illinois Dam 13 from April 1976 to August 1977. Precipitation data from NOAA (1974-1977).

general, toward well P-2 and the Plum River; however, there may be a local gradient toward the Plum River on the east side of the landfill.

Wells P-5 and P-6 were installed adjacent to each other at depths of 30 feet (9.14 m) and 45 feet (13.72 m) respectively to determine the vertical component of flow beneath the upland portion of the site. The slight differences between water levels in these two wells indicate that ground-water flow is predominantly in a lateral direction through the coarse sand and gravel deposits beneath the site. There appeared to be a small upward gradient (discharge condition); however, the data were not so precise as to prove this.

The hydraulic conductivity of the materials beneath the site was determined in the laboratory, and the results are included in appendix 9. The data confirm the permeable character of the alluvium; the hydraulic conductivity ranged from 2×10^{-3} cm/sec for sand to 8×10^{-4} cm/sec for pebbly sand.

To determine the rate of ground-water flow, Darcy's equation was used at Geneseo. Based on a hydraulic conductivity of 2×10^{-3} cm/sec and assuming an effective porosity of 0.30 for the alluvium, an effective (actual) velocity of 137 feet/yr (41.8 m/yr) was calculated for February 1977 at the edge of the fill near the Plum River, where gradients are steepest (.02 ft/ft). The corresponding effective velocity beneath the flat upland area of the fill (with a gradient of .002) is much slower, 13.7 feet/yr (4.2 m/yr).

Although the landfill is situated above the top of the zone of saturation, there is some evidence of saturation of the refuse. Leachate springs or seeps have developed along sides of the landfill. Standing puddles of leachate were periodically present along the operating face at the southern edge of the older fill area. Small seeps of brown, iron-stained leachate were also observed at the extreme northwestern corner of the landfill. As shown by Hughes, Landon, and Farvolden (1971), springs normally develop where the ground surface intercepts the top of the zone of saturation. This commonly occurs along the margin of a fill where the ground slopes more steeply than the slope of the ground-water mound. The presence of an unsaturated zone beneath the landfill shows that a ground-water mound does not extend up into the refuse. Infiltration through the permeable cover material, however, may have caused the refuse to reach field capacity. The leachate springs probably result when refuse at field capacity near the edge of the fill receives additional infiltration.

The Savanna landfill is situated in an environment that is generally considered unsuitable for solid-waste disposal. The site is underlain predominantly by permeable sand, gravel, and fractured dolomite bedrock, a setting which would appear to maximize the potential for pollution from waste disposal; however, this study indicates that no serious ground-water or surface-water pollution has been caused by the landfill. Although the shallow sand deposits represent a potentially significant water resource, ground water is generally available from deeper bedrock units. There are no data to indicate that the unconsolidated materials are being used as a source of water in the immediate area. The City of Savanna obtains water from deep wells ranging in depth from 1,300 to 1,500 feet (396 to 457 m) and provides water to residences in the immediate vicinity of the site.

Several factors have limited the impact of the landfill on nearby ground-water and surface-water resources. First, in the approximately eight years since filling began, a relatively small volume of refuse has been emplaced, thereby resulting in limited quantities of leachate. Second, the large volume of ground water flowing beneath the site and the flow in the Plum River would substantially dilute any leachate produced. Third, some attenuation occurs as leachate migrates away from the refuse (to be discussed later).

LYSIMETER INSTALLATION AND SAMPLING RESULTS

Eleven suction lysimeters were installed in six borings on or adjacent to the Savanna landfill. Installation data are summarized in appendix 2. Three lysimeters were placed

TABLE 5. Range of composition of soil moisture samples from lysimeters at the Savanna landfill.

	Uncontaminated				Contaminated			
	Minimum		Maximum		Minimum		Maximum	
	(mg/L)[a]	(meq/L)[b]	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Ca	119	5.94	217	10.83	126	6.29	756	37.72
Fe	0.1	0.004	0.2	0.008	0.1	0.004	85.0	0.03
Hg	<0.01	-	<.01	-	<.01	-	<.01	-
K	1.5	0.04	3.0	0.08	1.5	0.04	7.5	0.19
Mg	18.8	1.55	20.0	1.65	20	1.65	77	6.33
Na	5	0.22	17	0.74	17	0.74	430	18.71
Pb	<.01	-	<.01	-	<.01	-	<.01	-
Zn	<.01	0.00	0.01	0.001	0.01	0.001	0.36	0.011
Alk ($CaCO_3$)[c]	175	2.87	494	8.10	262	4.29	536	8.79
Cl	15	0.42	30	0.84	46	0.75	294	4.82
COD	4.0	-	15	-	15	-	396	-
NH_4-N	0.0	-	0.0	-	0.0	0.00	240	13.30
NO_3-N	0.6	0.01	172	2.77	0.4	0.010	2.0	0.005
pH[c]	6.45	-	6.75	-	6.40	-	6.85	-
SC[c]	850	-	1,100	-	1,130	-	2,100	-
SO_4	53	1.10	245	5.10	.01	0.00	78	1.62
TDS	960	-	1,050	-	1,910	-	2,671	-

[a]Except Hg (ppb), pH, and SC (μmhos).
[b]Milliequivalents per liter.
[c]Field measurement.

directly beneath the refuse. The remainder of the lysimeters were installed in borings surrounding and immediately adjacent to the landfill to determine the extent of lateral migration of leachate. The lysimeters at Savanna generally would not yield moisture samples for a period immediately following installation. Under unsaturated conditions, moisture in the vicinity of the lysimeter appears to require time to equilibrate with the initially dry silica sand surrounding the porous ceramic tip. This time period may range from a couple of weeks to several months.

WATER QUALITY

Ground water and surface water

Since 1974, data from routine analyses of chloride, iron, and total dissolved solids of samples from wells P-1, 2, and 3 have been submitted by the City of Savanna to the Illinois Environmental Protection Agency. Ground-water samples from wells P-1, 5, 6, and 7 were analyzed by the Illinois State Geological Survey. The results of chemical analyses of water samples from monitoring wells and the Plum River at Savanna are included in appendix 5.

These analyses give little indication of contamination by leachate. Chloride contamination is apparent only in well P-5. The storage of road salt in the vicinity of P-5 is believed to be responsible for the high concentrations of chloride, total dissolved solids, sodium, and calcium in this well. It is interesting to note that well P-5 is finished at a depth of 30 feet (9.1 m) whereas P-6, which is immediately adjacent to P-5 but is finished at a depth of 45 feet (13.7 m), has not yet been affected by the salt. The elevated value of COD (620 mg) from P-6 is questionable. Slightly elevated levels of total dissolved solids, sodium, calcium, specific conductivity, sulfate, and alkalinity in well P-7 may reflect shallow ground-water contamination immediately west of the landfill; however, this may have resulted from the infiltration of contaminated surface runoff from the adjacent steep side of the fill.

Surface-water samples were collected from the Plum River at two locations. One sample was taken upstream from the site, one-quarter mile to the northeast at Wacker Road. Another sample was taken downstream, near the railroad bridge, at the southwest corner of the site. For all practical purposes, there was no significant increase in the level of contamination as the river flowed past the landfill site.

Soil moisture

Appendix 5 includes the results of the chemical analyses of soil-moisture samples obtained with pressure-vacuum lysimeters at the Savanna landfill. Twenty-one samples obtained between May 27, 1976, and August 24, 1977, with an average volume of approximately 300 mL were analyzed. The results indicate that soil moisture in the vicinity of the landfill is distinctly more mineralized than ground water obtained from nearby monitoring wells.

The range in quality of soil moisture at the Savanna landfill is shown in table 5. Relative (meq/L) and absolute (ppm) concentrations for most ions indicate the nature of

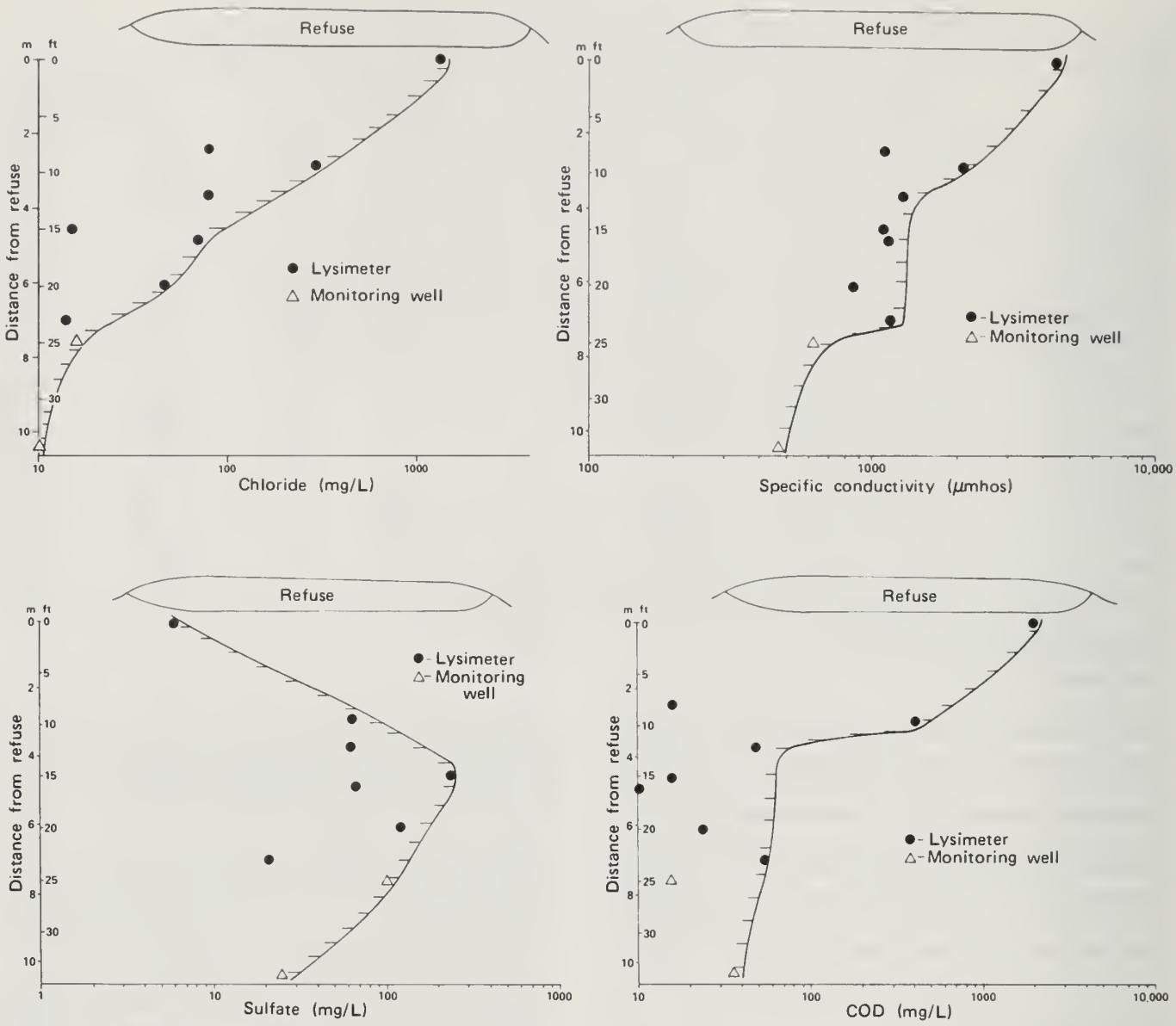
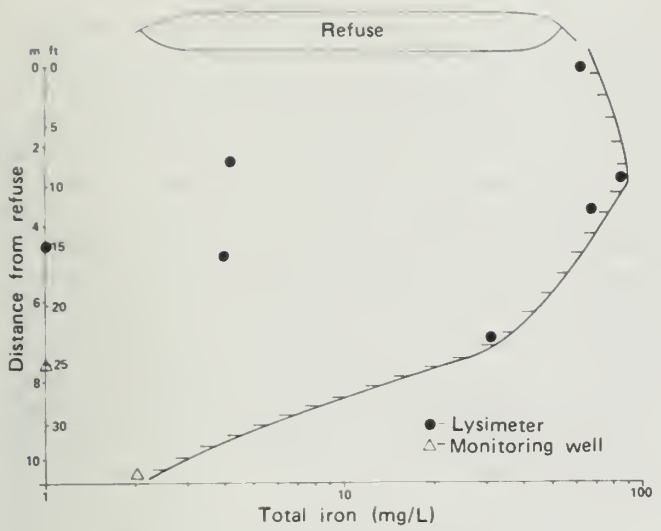


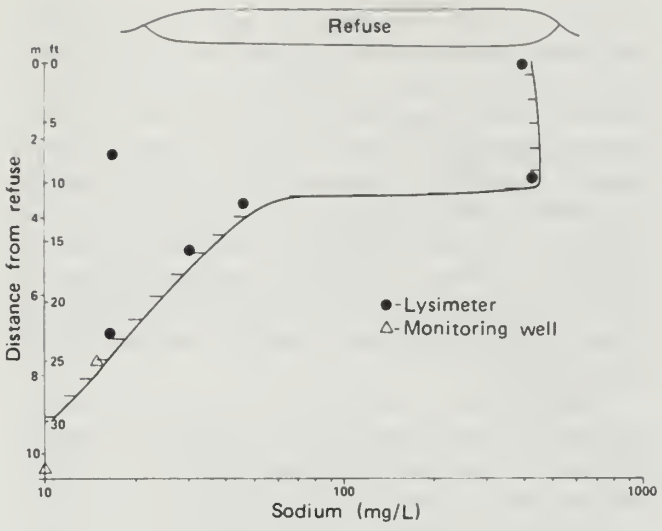
Figure 14. Concentrations of selected parameters as a function of distance from refuse in water beneath the Savanna landfill on March 17,1977. The hachured line represents the maximum concentration observed at the particular distance. The concentration at a depth of 0 feet represents leachate sampled from the refuse.

both contaminated and uncontaminated soil moisture. The order of minimum relative concentrations of uncontaminated soil moisture was in general: Ca> Alkalinity> Mg> SO_4 > Cl> Na> K. The maximum relative concentrations of apparently uncontaminated soil moisture were very similar: Ca> Alkalinity> Mg> SO_4 > NO_3 > Mg> Cl> Na> K. This may reflect local contamination by sulfate and nitrate from the landfill. The pH of uncontaminated soil moisture ranged from 6.45 to 6.75. Contaminated soil moisture generally had maximum relative concentrations in the decreasing order: Ca> Na> NH_3 > Alkalinity > Mg> Cl > SO_4 > K. The pH of contaminated soil moisture, from 6.40 to 6.85, was similar to that of uncontaminated samples. Elevated concentrations of ammonia were present only in leachate samples from a lysimeter (S-2) within the refuse.

Many samples of soil moisture contained elevated levels of one or more parameters suggesting a wide, diffuse area of influence of the landfill.

Effect of distance from refuse on soil-moisture quality. The quality of soil moisture and ground water beneath or adjacent to the landfill on March 17, 1977, is illustrated in figure 14. Shown in each diagram is a general cross-sectional profile of the landfill. The hachured line indicates the maximum concentrations observed at that particular depth. It should be noted that the concentration of each parameter is plotted on a logarithmic scale versus distance from the refuse. The concentration of each parameter at an indicated depth of 0 feet represents leachate obtained from lysimeter S-2-SL-1 placed within refuse that is approximately 8 years old and is near the base of the fill.





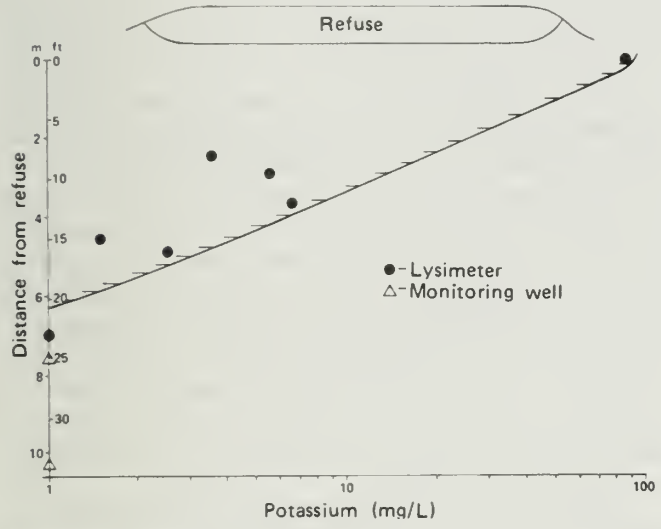


Figure 14. *(continued)* ISGS 1979

The diagrams show the differential migration of various species in leachate below the refuse. Concentrations of chloride, among the most mobile of ions, and specific conductivity, which reflects total ionic species, decreased steadily with distance from the refuse. Dilution and dispersion may have been partly responsible for this apparent attenuation with distance from the refuse. COD concentrations in the vicinity of the landfill decreased rapidly to a distance of 12 feet (4 m) from the refuse. Beyond this distance, COD concentrations were variable and occasionally reflected a greater degree of contamination than chloride does for the same depth. There have been no apparent reductions in the levels of chloride, specific conductance, and COD released by the landfill. This indicates that infiltration in the vicinity of the landfill has continued to produce leachate. The maximum concentrations of chloride, COD, and specific conductivity were all found in samples of leachate from a lysimeter in the refuse.

Very low concentrations of sulfate were found in relatively anaerobic samples near the refuse; the maximum concentration of sulfate occurred at a distance of about 16 feet (5 m) from the landfill. Nitrate behaved similarly whereas the maximum concentrations of ammonia were in leachate samples from refuse. Significant attenuation of ammonia beneath the refuse may have resulted from cation exchange reactions. Sulfate concentrations essentially at background levels were found in ground water at a distance of 35 feet (10 m) from the refuse.

Levels of sodium at a depth of 10 feet (3 m) were nearly identical to those in raw leachate; this indicates the continued release of sodium from the refuse in response to infiltration. Concentrations of sodium decreased steadily beyond a distance of 10 feet (3 m), possibly also reflecting dilution and dispersion of soil moisture and ground water.

Iron concentrations reached a maximum of 85 mg/L at a distance of 10 feet (3 m) from the refuse and remained about 10 mg/L to a depth of 26 feet (8 m). Below this depth, concentrations of iron in ground water were below 3 mg/L. It appears that the production of iron by the refuse may have decreased slightly. Measurements of Eh indicated, however, that the most anaerobic conditions were in samples of leachate and that soil water becomes progressively more oxidized with distance from the refuse. Under these conditions, iron and manganese maxima should be associated with the most anaerobic leachate from the refuse. The lowest concentrations of iron were generally associated with higher values of Eh and pH, indicating that the removal of iron was caused by precipitation of iron oxides or hydroxides.

Potassium concentrations decreased sharply with distance from the refuse, reaching background values of essentially 1 mg/L at a distance of 20 feet (6 m). Potassium is apparently migrating at a very slow rate, possibly due to absorption processes in the soil.

Variation in quality of soil moisture with time and distance from refuse. Samples were collected from the lysimeters at Savanna from May 27, 1976, to August 25, 1977, at intervals ranging from 33 to 270 days. Because refuse emplacement began in 1967, it was not possible to study long-term changes in leachate quality with depth beneath the Savanna landfill; however, lysimeter S-4-SL-1 was placed at a depth of 10 feet (3 m) immediately prior to the burial of refuse in the most recently filled portion of the site. Using this lysimeter and others in the immediate vicinity, attempts were made to monitor the initial effects of waste disposal.

Plots of the concentrations of chloride, sodium, potassium, and iron versus time are presented in figure 15. Although the data are limited and, therefore, do not reflect long-term changes in concentrations, it was possible to determine the relative quality of leachate-soil moisture with time and distance from the refuse. In each diagram, S-2-SL-1 represents samples of leachate from a lysimeter placed within the refuse. The graphs show that recently produced leachate was generally contaminated more than soil moisture beneath the refuse.

Lysimeter S-1-SL-1 is situated in the northeastern corner of the fill at a depth of 9.5 feet (2.9 m) beneath refuse emplaced in 1976. Samples from this lysimeter were generally more contaminated than any other samples of soil moisture. Leachate-soil moisture collected on March 17, 1977, from lysimeter S-1-SL-1 even contained more sodium and iron than raw leachate.

Lysimeter S-4-SL-1 is also situated beneath the refuse; however, it was installed in the underlying sand immediately prior to the emplacement of refuse. Three samples of soil moisture were obtained within one year following burial. Although there undoubtedly was moisture originally present in the sand beneath the refuse, the consistent, relatively high volumes in the samples indicate that moisture moved from the refuse toward the lysimeter. This moisture may have resulted from compaction of the refuse, infiltration through the refuse, or infiltration adjacent to the landfill. The character of the leachate from S-4-SL-1 did not change markedly from July 1976 to March 1977; however, the elevated levels of chloride, potassium, and iron indicate contamination from waste disposal. Although the overlying refuse did not have sufficient time to reach field capacity, the soil moisture samples may have resulted from the channeling of infiltration through the refuse into the underlying sand, without allowing the leachate to become highly mineralized. Another explanation is suggested by samples from lysimeters installed adjacent to the landfill, but not directly beneath refuse. Samples from some of these lysimeters clearly show contamination by leachate that apparently migrated laterally from the adjacent refuse. Contaminated surface runoff from the landfill may also have infiltrated in the vicinity of lysimeters adjacent to the landfill.

Some lysimeters adjacent to the landfill indicate contamination by leachate, although others are essentially uncontaminated. Generally, where two lysimeters were installed in a single boring, soil moisture from the shallow lysimeter was more contaminated than deeper soil moisture. In boring S-6, at the southeastern corner of the landfill, the shallow lysimeter (SL-2) at a depth of 12 feet (3.7 m) is probably only 10 feet (3 m) from the refuse. Samples from this lysimeter showed quite clearly contamination by chloride, sodium, potassium, and iron. Sodium concentrations increased dramatically from February 9 to March 17, 1977, from 10 to 47 mg/L, probably in response to recharge from snowmelt and increased precipitation. The deeper lysimeter (S-6-SL-1), on the other hand, showed that soil moisture at a depth of 22 feet (6.7 m) is less contaminated, although it still contained high concentrations of iron.

The two lysimeters in boring S-3 adjacent to the northwestern side of the landfill showed the reverse situation, however. Soil moisture from the deeper of the two (SL-1), at a depth of 19 feet (5.8 m), was more contaminated than that from the shallower lysimeter (SL-2) at a depth of 9 feet (2.7 m). In this case, the nearby refuse is probably 16 feet (5 m) in depth and the boring is only 10 feet (3 m) away. The upper lysimeter (SL-2) is probably so shallow that it intercepts infiltration through the overlying, permeable sands—water that has not come in contact with the refuse. Thus, the changes in concentrations of chloride, sodium, and potassium probably reflect the variable quality of soil-moisture. The deeper lysimeter (SL-1) is very near the refuse and appeared to show the effects of leachate migration through the unsaturated sand adjacent to the refuse. The concentrations of iron in both shallow and deep soil moisture, however, were very low, possibly indicating the influence of more oxidizing conditions in the unsaturated soils adjacent to the refuse.

The lysimeter in S-7, north of the landfill, yielded soil-moisture samples very similar in composition to relatively uncontaminated water samples from S-3-SL-2 and S-6-SL-1. Ground water appears to be flowing in a southwesterly direction beneath the site; therefore S-7 is on the upgradient side of the landfill approximately 26 feet (8 m) from the refuse. At first glance, the composition of soil-moisture samples at a distance of 25 feet (7.5 m) from the refuse in figure 15 appears to reflect background water quality. An exception was the relatively high, increasing concentration of iron in S-7 from February to March 1977, from 8.5 to 31 mg/L. Although chloride concentrations are very low, a COD level of 53 mg/L may indicate leachate contamination.

No lead or mercury was detected in any water samples, and zinc was present in soil moisture from only three lysimeters. Zinc concentrations were consistently high in S-4-SL-1, the lysimster installed beneath the most recent refuse, and in S-3-SL-2, which contained elevated levels of nitrate, sulfate, and zinc.

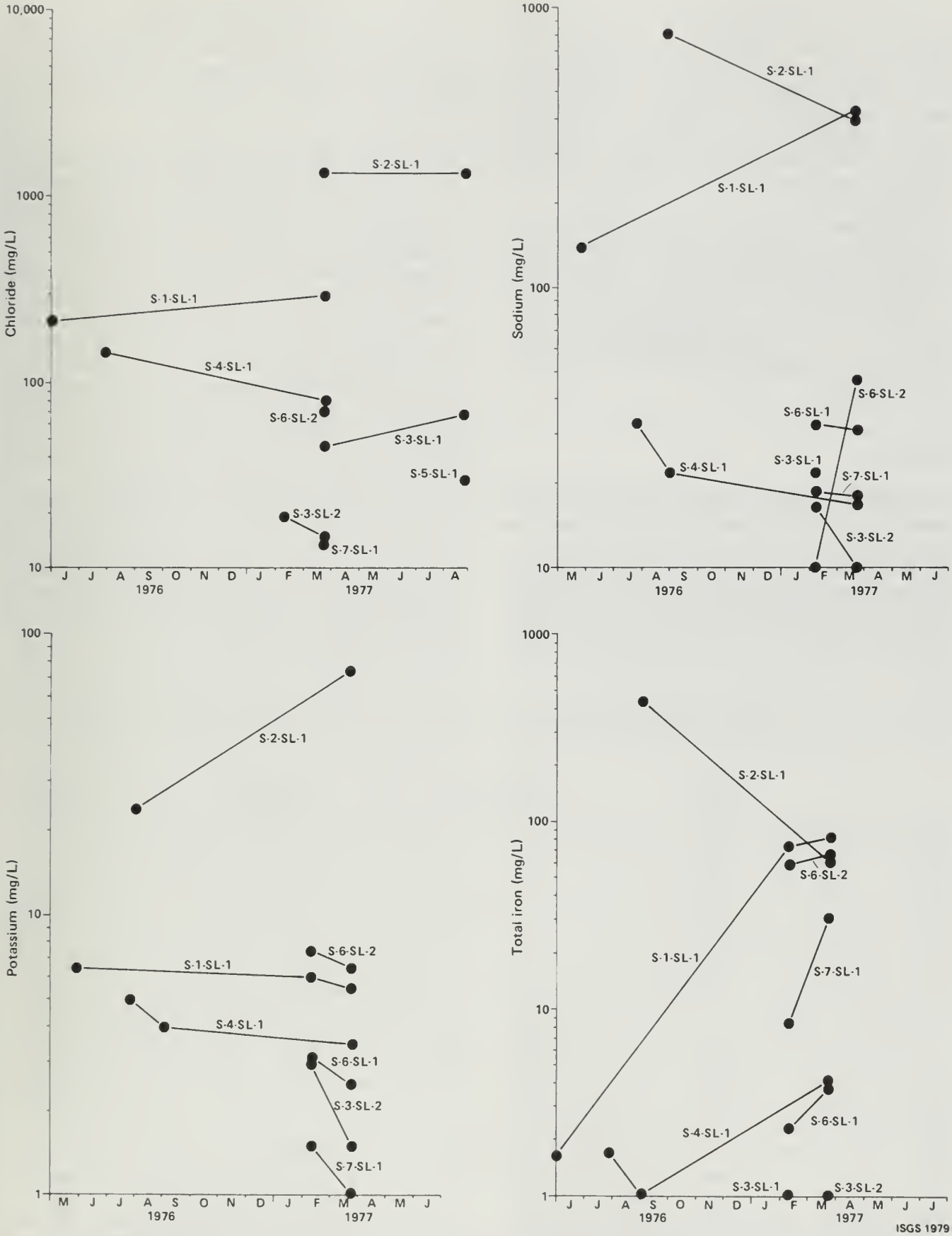


Figure 15. Changes in concentrations of selected parameters with time in soil moisture from lysimeters at the Savanna landfill. S-2-SL-1 represents leachate sampled from the refuse. S-1-SL-2 represents suction lysimeter number 2 in boring S-1.

The lysimeters indicate that, in addition to vertical migration downward beneath the refuse, leachate affects the unsaturated materials adjacent to the refuse. Refuse at field capacity probably has a greater moisture content than the surrounding soils. Additonal infiltration causes leachate to flow away from the refuse, predominantly toward the water table, but also laterally from the fill; it can influence an area at least 10 to 15 feet (3 to 5 m) away from the refuse.

The diagrams indicate that maximum concentrations of chloride have been reduced by approximately 78 percent at a depth of 9.5 feet (2.9 m) in S-1-SL-1 directly beneath 5- to 8-year-old refuse. On the other hand, leachate migrating laterally from the fill is more susceptible to dilution by direct infiltration. Maximum chloride concentrations are reduced by more than 95 percent within 10 to 15 feet (3 to 5 m) of the fill.

SUMMARY

Table 6 illustrates the typical composition of leachate, contaminated and uncontaminated soil moisture, and ground water beneath the Savanna landfill. Except for a few parameters, such as calcium, alkalinity, sodium, and COD, the quality of ground water from well P-7 is similar to that of uncontaminated soil moisture. The composition of moisture sampled from the refuse with a lysimeter (S-2) is typical of raw leachate. The difference between the composition of raw leachate and contaminated soil moisture probably reflects the degree of attenuation resulting from migration through the unsaturated materials beneath the landfill.

The distribution of major cations in ground water and soil moisture at the Savanna landfill is shown in figure 16. Represented by relative percentages of milliequivalents per liter, soil moisture in general contains a greater percentage of calcium and less magnesium than ground water. The composition of surface water from the Plum River is very similar to that of nearby ground water. Leachate collected from the refuse (S-2) has a greater relative percentage of sodium plus potassium; however, leachate-contaminated soil moisture collected beneath the refuse has a composition within the region characteristic of uncontaminated ground water. Well P-5 also contains a much greater relative percentage of sodium plus potassium; however, this is not indicative of contamination by leachate. The leaching of nearby uncovered piles of road salt has resulted in shallow ground-water pollution by sodium and chloride.

The relative distribution of major anions is also shown in figure 16. Uncontaminated ground water and soil moisture are similar in composition, although soil moisture affected by leachate contains relatively more chloride. Highly contaminated, raw leachate has a high content of chloride, but well P-5 shows the effects of the salt pollution, not leachate contamination.

TABLE 6. Composition of leachate, soil moisture, and ground water at the Savanna landfill.

	S-1-SL-1 Leachate (mg/L)[a]	S-2 Contaminated soil moisture (mg/L)	Uncontaminated soil moisture (mg/L)	Ground water (P-8) (mg/L)
Ca	5,600	756	119	75
Fe	450	85	0.2	0.3
Hg	<.2 ppb	<.2 ppb	<.2 ppb	<.2 ppb
K	85	6.5	3.0	3.5
Mg	900	77	19	19
Na	820	430	16	5
Pb	0.10	<.01	<.01	<.01
Zn	0.9	0.2	0.05	0.08
Alk ($CaCO_3$)[b]	440	536	262	223
Cl	1,326	294	15	16
COD	1,944	396	10	15
NH_4-N	240	-	0.0	0.3
NO_3-N	0.7	2.0	0.4	0.4
pH[b]	6.80	7.02	6.68	7.05
SC[b]	6,200	2,100	850	600
SO_4	6	78	58	25
TDS	5,583	2,671	1,051	320

[a]Except Hg (ppb), pH, and SC (μmhos).
[b]Field measurement.

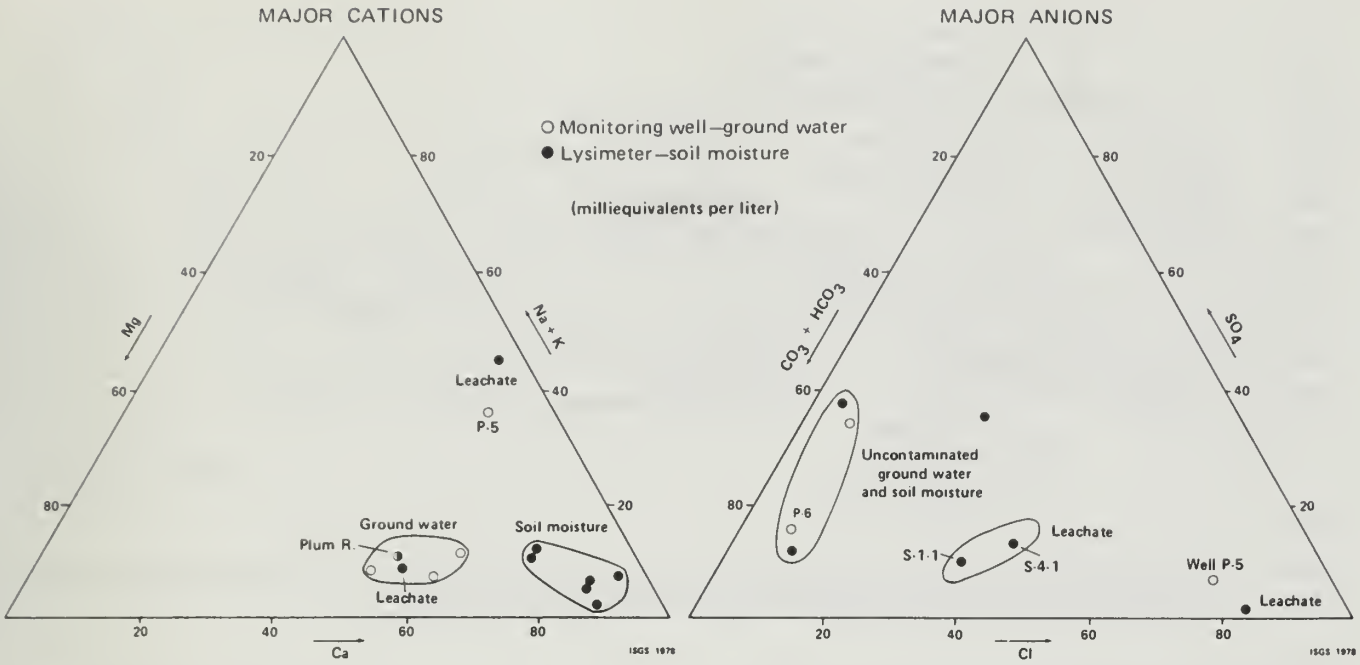


Figure 16. Distribution of major cations and anions in soil moisture and ground water at the Savanna landfill. Results are in milliequivalents per liter.

SOIL CHEMISTRY

The Savanna landfill is underlain by alluvial deposits of silty clay to sand and gravel and clay contents of 0 to 67 percent. The majority of the site is directly underlain by sand and silty sand deposits and has occasional lenses of sandy silt that are 2 to 6 inches (5 to 15 cm) thick. The clay mineralogy of the lenses of fine-grained silt is: approximately 64 percent expandables, 22 percent illite, and 12 percent chlorite plus kaolinite. Cation exchange capacities range from 1.1 to 2.3 milliequivalents per 100 grams of soil (meq/100 g) for fine-grained silty and clayey materials. As in the case of the Geneso landfill, the materials beneath this site having the highest CEC are limited to thin (1 to 3 in. [2.5 to 7.6 cm]) lenses of silty material interbedded with sand and gravel, which itself has virtually no ion-exchange capacity. Thick deposits of silty clay having a CEC of 10.7 meq/100 grams were encountered in boring P-4; however, these are at depths of 30 to 50 feet (9.1 to 15.2 m) beneath the refuse and 20 feet (6.1 m) below the water table. Shallow ground water beneath the site probably flows through the coarse alluvial sand deposits toward the Plum River. Leachate would probably not pass through the deeper, fine-grained material, thus limiting the potential for attenuation.

Chemical analyses were made of 10 soil samples from Savanna. The results, in total concentrations, are presented in appendix 3. Samples from boring S-1 are from directly beneath refuse emplaced in 1967. Boring P-4 is 20 feet (6.1 m) west of the landfill and P-5 is 50 feet (15 m) east of the fill. Soil samples from both P-4 and P-5 should be relatively unaffected by leachate contamination. Few differences are apparent in chemical composition between leachate-affected sediments beneath the fill in S-1 and presumably uncontaminated samples from P-4 and P-5. Chloride concentrations in soil samples from P-5 are much higher than background levels. This is the result of infiltration of runoff from the piles of road salt stored nearby. Concentrations of chloride of 0.62 percent and 0.35 percent were found at depths of 6 and 7 feet (1.8 and 2.1 m) respectively although the concentration at a depth of 13 feet (4 m) was essentially at background level (.04 percent).

Carbonates were leached to a depth of 6 feet (1.8 m) in P-5; however, the remaining materials are calcareous and probably contain clay minerals that are predominantly calcium saturated. Calcium concentrations in calcareous samples varied from 1.13 to 4.59 percent and magnesium ranged from 0.51 to 2.39 percent, the highest concentrations of each associated with fine-grained silty clay and silty sand material. Because of the relatively high content of calcium and magnesium in soils beneath the landfill, one would expect to see a displacement of calcium and magnesium from the exchange sites of clay minerals upon interaction with highly mineralized leachate.

Lead and sulfate were all below the limits of detection (22 ppm and 0.01 ppm respectively). Mercury concentrations ranged from 0.02 to 0.07 ppm and showed no discernible difference between contaminated and uncontaminated samples. Elevated concentrations of iron and potassium were associated with increased content of silt and clay and appear to be unrelated to the degree of sample contamination. Sodium concentrations showed no obvious trends.

Contamination of soil samples in S-1 may be indicated

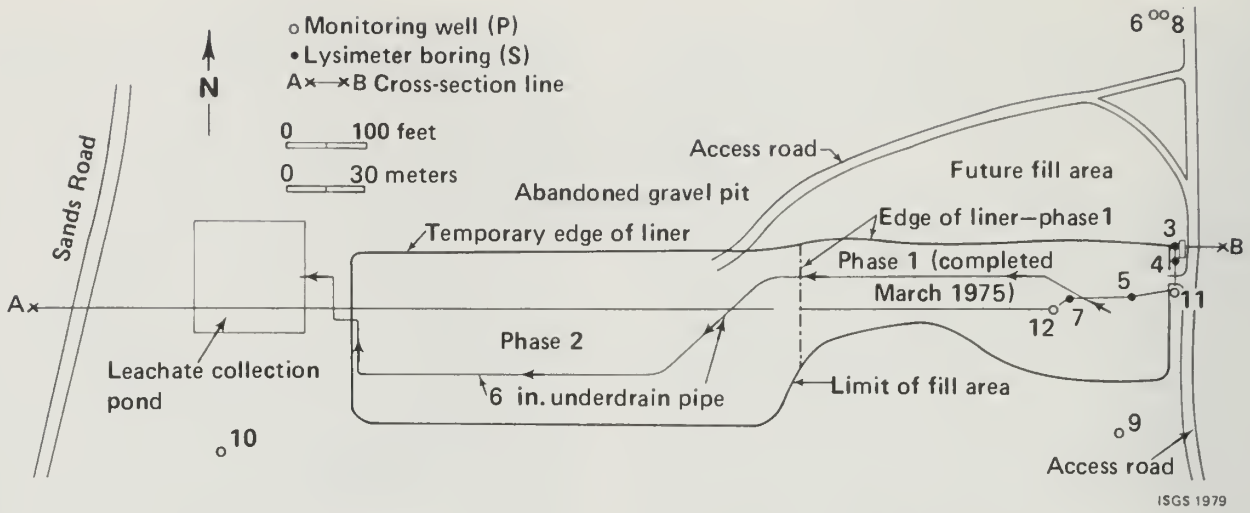


Figure 17. Map of Crystal Lake landfill showing locations of monitoring wells and lysimeter borings. The leachate collection system consists of a clay liner and an underdrain pipe which discharges into the leachate collection pond.

by average concentrations of zinc of 43 ppm for four samples. Six samples from P-4 and P-5 average 23 ppm. A sample of sand from S-1 at a depth of 5 feet (1.5 m) below the refuse contained 52 ppm zinc. This relatively high concentration of zinc is the only apparent indication of contamination by leachate of soil samples at the Savanna landfill.

CRYSTAL LAKE LANDFILL

DESCRIPTION OF SITE

The Crystal Lake landfill is located in McHenry County in northeastern Illinois (fig. 1) in the NE¼SE¼ Sec. 3, T. 43 N., R. 8 E., east of Sands Road. The site is situated on the broad, irregular West Chicago Moraine southeast of Crystal Lake, Illinois. The topography is rolling with rounded hills (kames) and depressions (kettles). The elevation of the landfill is between 840 and 900 feet (256 and 274 m) above sea level. Figure 17 is a general map of the landfill. The surrounding area to the west and south of the landfill is characterized by broad till-covered outwash plains 850 to 900 feet (259 to 274 m) in elevation. The area to the east has been eroded, is generally lower in elevation, 810 to 850 feet (247 to 259 m), and has numerous lakes and swampy lowland areas.

The site itself consists of 40 acres (16 ha) in an abandoned gravel pit which was not reclaimed following the removal of sand and gravel during the 1930s. Instead, narrow ridges of spoil material, predominantly glacial till, remain. The landfill began operation in the southern portion of the site where the spoil material and the underlying silty sand were excavated to a depth of 15 to 20 feet (5 to 6 m) prior to the installation of an artificial clay liner. The refuse was to be underlain by a clay liner consisting of bentonite clay (montmorillonite) and a mixture of fine-grained materials from the spoil piles on the site. A leachate collection system, consisting of a 6-inch (15.2 cm) in diameter pipe, was to be installed above the line to discharge into a bentonite-lined lagoon at the west end of the fill area. Geswein (1975) discusses the use of liners for land disposal sites and includes this site.

A permit for this site was received from the Illinois Environmental Protection Agency (IEPA) in August 1972, and by December 1973 the first portion of the site had been prepared for waste disposal. The eastern portion of the site was graded with a gradual slope to the west and a total of approximately 0.4 inch (1 cm) of bentonite clay was spread over the underlying sand. Reportedly, precipitation was relied upon to wet, or hydrate, the clay and bring it to optimum moisture content. This bentonite was manufactured by American Colloid, Inc. under the trade name of Volclay SG-40. Volclay SG-40 was used on the eastern half of the disposal area and by July 1977, on approximately one-third of the western half. Approximately 2 feet (0.6 m) of glacial till and topsoil from the surrounding spoil piles was then placed over the bentonite and compacted. Although this material contained some fine-grained silt and clay, it also contained much sand and many cobbles and boulders to 6 inches (15 cm) in diameter, which were not removed prior to installation of the liner. Compaction of this portion of the liner may have affected the continuity of the underlying layer of bentonite. During subsequent excavations a portion of the refuse, clay liner, and the underlying silty sand was exposed (fig. 18) along the northern edge of the initial fill area. Emplacement of refuse was begun in December 1973, progressing from east to west over the first portion of the liner.

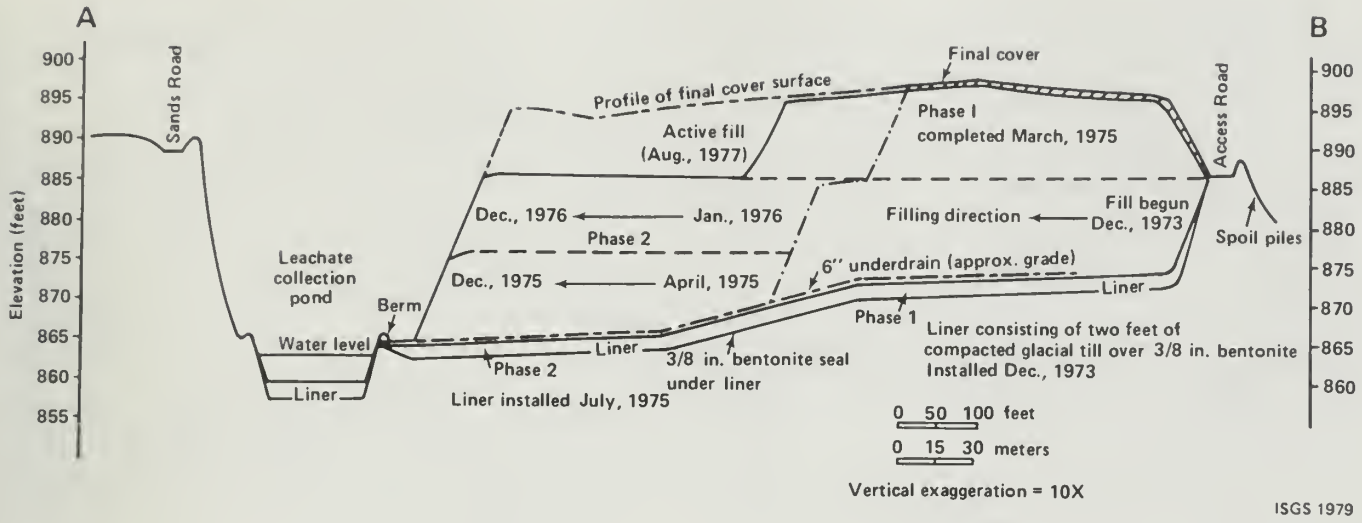


Figure 19. East-west cross section A-B of the Crystal Lake landfill showing the general filling sequence and liner construction.

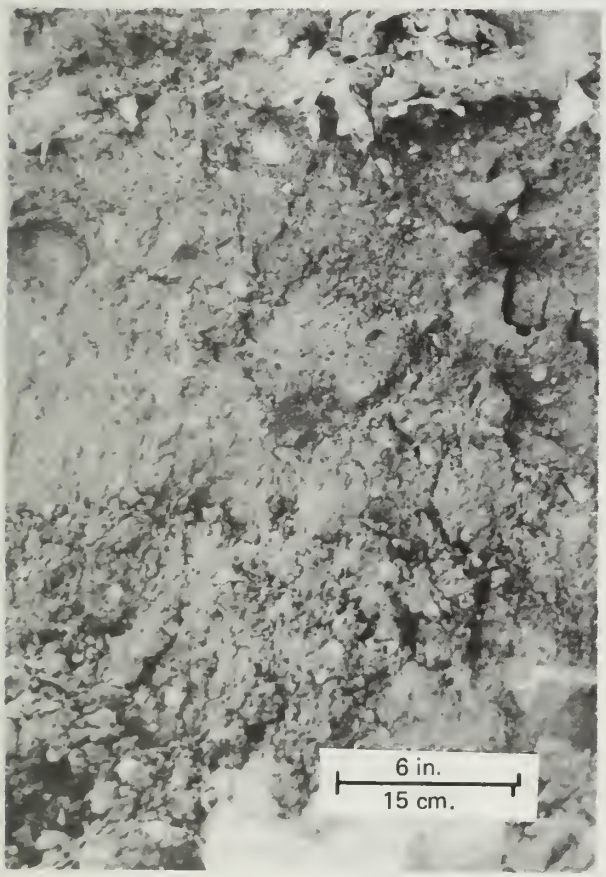


Figure 18. Exposure of glacial till liner at base of Crystal Lake landfill and the underlying silty sand. A thin seam of bentonite clay is present between the till and the sand. The till is fractured and contains numerous cobbles. The dark stain in the center is leachate on the face of a fracture.

During the operation of this portion of the landfill, the manufacturer determined that the bentonite clay (Volclay SG-40) used in the liner was susceptible to chemical attack by leachate, which would thus reduce its effectiveness (Hughes, 1975). Tests by the Illinois Environmental Protection Agency (personal communication, 1975) confirmed the SG-40 bentonite "was destroyed by leachate in a short period of time." Laboratory tests were subsequently conducted of more "contaminant-resistant" bentonite by the Illinois Environmental Protection Agency. These tests utilized a 1-foot (30.5 cm) column of a mixture of bentonite and sand at optimum moisture content and density to simulate the thin layer of bentonite spread over the sand beneath the landfill. The laboratory tests of this "contaminant-resistant" bentonite indicated that leachate traveled approximately 1 inch (2.54 cm) per month through the seal and began to leak from the seal in approximately 1 year (personal communication, 1975).

In April 1975 a liner was placed over the remainder of the first disposal area. A more contaminant-resistant variety of bentonite (Volclay SLS-70) was spread in a thin layer and was covered by a 2 foot (0.6 m) thick mixture of compacted glacial till and topsoil. Filling began shortly thereafter and by mid-1977 more than 50 feet (15 m) of refuse had been placed over the first portion of the landfill. Figures 19 and 20 are cross sections that illustrate the sequence of filling and the relationships of monitoring devices to the refuse and the liner.

On October 27, 1976, the site received a permit to develop the next portion of the site immediately to the north of the existing landfill. The initial plans were to operate this next portion in a similar manner and to extend the liner beneath the new fill area. The new permit from the IEPA, however, required that at least 5 feet (1.5 m) of low-permeability clay be used as a liner and similar material

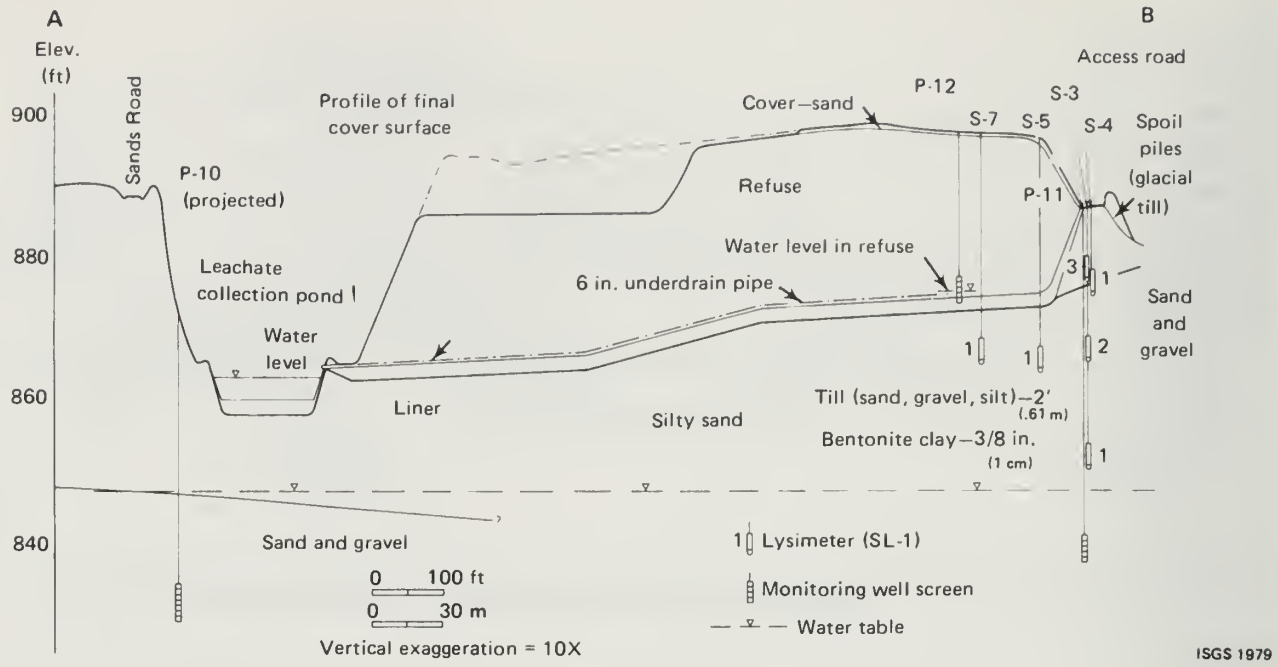


Figure 20. East-west cross section A-B of the Crystal Lake landfill showing the liner and relationships of monitoring devices to underlying materials. The base of the landfill slopes toward the west while the water table slopes gradually toward the east.

was to be used to cover the site upon completion. There also is no leachate-collection system beneath the new fill area. Filling of the new area began in 1979.

The majority of the fill material consists of general household refuse from the Crystal Lake vicinity, but industries in the area contribute appreciable quantities of miscellaneous refuse. A temporary cover consisting mainly of sandy glacial till was placed over the eastern portion of the site in 1977 and some vegetation is present. The upper surface of the fill is relatively flat, rising 20 to 50 feet (6 to 15 m) above the surrounding area. The sides of the fill are quite steep, and the stony, sandy imtermediate cover material has eroded along portions of the fill edge. Leachate springs have also been observed on the northeast and southwest faces of the fill.

GEOLOGY

The Crystal Lake landfill is situated amid the West Chicago Moraine, which overlies a thick deposit of silt and fine- to coarse-grained sand and gravel deposited in a broad outwash plain by glacial meltwater. The site is directly underlain by 50 to 65 feet (15 to 20 m) of silty sand to sand and gravel that becomes coarser with depth. The silty and sandy Tiskilwa Till separates the overlying outwash, in which the landfill is situated, from underlying medium- to coarse-grained sand and gravel deposits and Silurian dolomite bedrock, both of which are significant aquifers. Isolated patches of Haeger Till, which comprises much of the West Chicago Moraine, are present at the surface generally less than 10 feet (3 m) in thickness. At the landfill site, the glacial till (Haeger) was removed prior to sand and gravel excavation. The total thickness of glacial drift beneath the site is approximately 250 feet (75 m).

Descriptions of the borings made during this study are included in appendix 7; laboratory data from selected borings are presented in appendix 8. Table 7 summarizes the data for texture, mineralogy, and cation exchange capcaity for the landfill liner and underlying materials. A brief description of each stratigraphic unit is as follows:

Quaternary System
Pleistocene Series
Wisconsinan Stage
Wedron Formation

Haeger Till Member (0 to 10 feet [0 to 3 m] thick)

Sandy, gravelly, buff till. Clay mineralogy and texture similar to that of underlying sand and gravel deposits. Comprises majority of spoil piles on site and is mixed with more clayey top soil formerly developed on its surface. Noncalcareous. Used as liner beneath landfill.

Henry Formation Outwash (50 to 65 feet [15 to 20 m] thick)

Interbedded, stratified deposits of silt, fine to coarse sand, gravel, and cobbles associated with Haeger Till. Upper 33 feet (10 m) fine, silty sand to fine sand becoming coarser with depth. Upper 10 feet (3 m) may have consisted of coarse sand and gravel that was removed during

TABLE 7. Mean texture, clay mineralogy, and range of cation exchange capacity (CEC) of materials beneath the Crystal Lake landfill.

Material	Texture[a] Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Clay mineralogy[b] Ex (%)	I (%)	C + K (%)	CEC[c]
Haeger Till	30	50	40	10	12	67	21	2.5-4.5[d]
Top soil in till	-	-	-	-	45	38	17	--
Sand	0-20	88	6	6	-	-	-	0.8-1.1
Silty sand	0	56	37	7	-	-	-	0.9-1.1
Sandy silt	0	33	61	6	-	-	-	1.3
Silt	0	7	87	6	-	-	-	1.4

[a]Gravel, 2 mm; sand, 2 to 0.0625 mm; silt, 0.0625 to .0039 mm; clay, <.0039 mm.
[b]Ex = Expandables; I = Illite; C + K = Chlorite plus kaolinite.
[c]Milliequivalents per 100 g dry soil.
[d]Samples include a mixture of till and top soil material.

mining. Calcareous. Lower portion potentially important aquifer. Directly underlies landfill.

Wedron Formation

Tiskilwa Till Member (65 to 100 feet [20 to 30 m] thick)

Thick, homogeneous, pink, silty, sandy till present throughout the area. Calcareous. Isolates surficial outwash from underlying sand and gravel and dolomite aquifers.

Outwash (75 to 100 feet [23 to 30 m] thick)

Interbedded silt, medium to coarse sand, and sand and gravel. Major aquifer.

Silurian System

Niagaran Series

Dolomite bedrock, fractured, possibly greater than 100 feet (30 m) thick. Major aquifer.

HYDROGEOLOGY

Three monitoring wells were installed during this study to complement the four existing observation wells in the vicinity of the landfill (fig. 17). Installation data for each well are included in appendix 1.

Records from shallow wells P-9 and P-11 adjacent to the landfill indicate that the water table varied from 25 to 33 feet (7.6 to 10 m) beneath the base of the refuse. Figure 21 shows the changes in water levels and average monthly precipitation from November 1974 to August 1977. Water levels in all wells except P-12, which is installed at the base of the refuse, behaved similarly. Water levels have declined steadily since the spring of 1976 in response to reduced precipitation and continued groundwater withdrawal, declining approximately 5 feet (1.52 m) in a year and a half. Increased precipitation in the spring of 1977 had no apparent effect on water levels except those in P-12. Water levels in P-12 at that time reflected the accumulation of leachate above the liner and within the refuse. This well responded to increased infiltration from rainfall during 1977 and indicated that 2 feet (0.6 m) of leachate-saturated refuse was present over the liner on August 23, 1977.

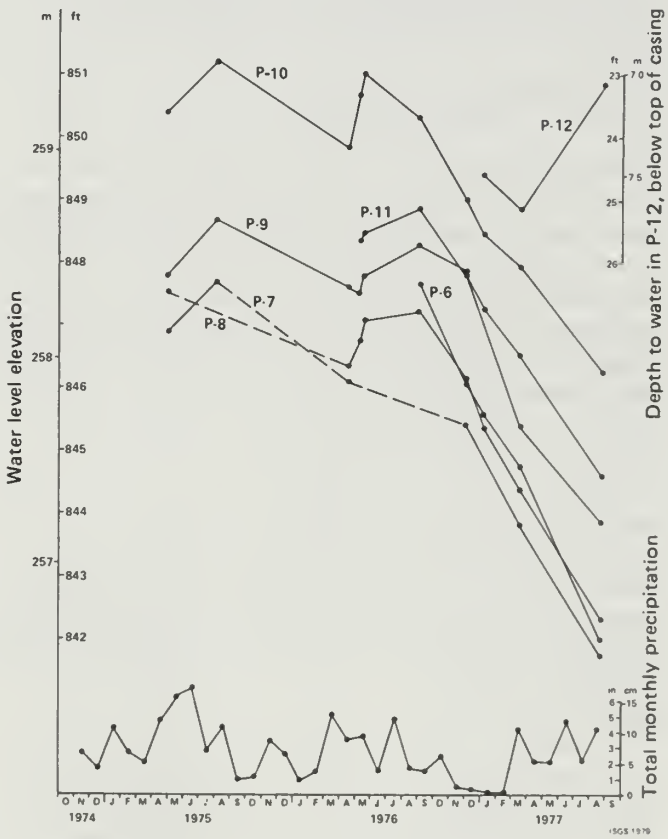


Figure 21. Water level changes in monitoring wells at the Crystal Lake landfill and precipitation at Elgin, Illinois, from November 1974 to August 1977. Precipitation data from NOAA (1974-1977).

The monitoring wells indicated an easterly flow of shallow ground-water in the outwash sand immediately beneath the site in response to a relatively flat hydraulic gradient. It should be noted that, although ground-water flow is apparently toward the east, the base of the landfill is graded toward the leachate collection pond to the west. The relatively large thickness of fill material will probably alter the flow system in the future to some degree, especially as the fill area grows.

The direction of flow in the underlying Silurian dolomite aquifer is toward the southwest as measured by Testing Engineers, Inc. in July 1972. Water levels in wells cased into the dolomite bedrock in the upland area surrounding the site were approximately 33 feet (10 m) lower than shallow water levels, indicating a downward vertical gradient (recharge conditions). The intervening, fine-grained Tiskilwa Till, however, limits the degree of hydrologic connection between these two aquifers and, thus, reduces the potential for contamination of the underlying aquifer. The primary component of shallow ground-water flow is probably lateral in response to gradients toward Lake Killarney or the Fox River to the east. Using a hydraulic conductivity of 1.5×10^{-4} cm/sec for the sand beneath the site, a gradient of .002 ft/ft, and assuming an effective porosity of 0.03, an effective (actual) velocity of 0.1 feet/yr (0.03 m/yr) was calculated. Larger gradients are present in the vicinity of Lake Killarney to the east of the site.

EFFECTIVENESS OF LINER

The initial investigation in 1972 by Testing Engineers, Inc. (1972), which determined the suitability of the site, proposed that the landfill be lined with a "minimum of 3 feet (1 m) of silty soil from the spoil piles which should be compacted to at least 95 percent of maximum density at optimum moisture content." Laboratory tests indicated a hydraulic conductivity of 1.5×10^{-7} cm/sec for a sample from the spoil piles at 100 percent maximum density. The report also suggested that the hydraulic conductivity of material from the spoil piles could vary considerably with changes in texture. The results of initial calculations of seepage indicated that approximately 11 percent of all water entering the landfill would escape through the liner, assuming that the refuse had reached field capacity. If the actual hydraulic conductivity of the liner were an order of magnitude higher, however, this report predicted that all infiltration would theoretically escape under similar circumstances.

Laboratory tests of hydraulic conductivity were run during this study on three samples from the Crystal Lake landfill. The results are included in appendix 9. A sample of the till liner encountered in boring S-7 had a computed hydraulic conductivity of 6.6×10^{-7} cm/sec; however, this sample did not contain any bentonite or large pebbles. Bentonite undoubtedly has a very low hydraulic conductivity; however, at this site, its effectiveness is reduced because it consists of only a very thin layer that is compacted by the overlying glacial till and refuse and may be locally disturbed. Fortunately, the underlying materials are not as permeable as first thought. Tests of a sample of the silty sand from immediately beneath the liner in S-7 indicated a hydraulic conductivity of 2.3×10^{-6} cm/sec. A sample of sandy silt from P-6 at a depth of 31 feet (9.5 m) had a hydraulic conductivity of 1.5×10^{-4} cm/sec. The coarse-grained sand and gravel deposits at depths of 50 to 65 feet (15 to 20 m) are probably more permeable.

The liner and underdrain system installed beneath the refuse were designed to collect leachate accumulating at the base of the refuse and to direct it to the collection pond, where it could be recovered and treated; however, in the first four years after refuse emplacement, the drain pipe yielded water only during heavy rainfalls. This water appeared visually to be relatively uncontaminated. If the refuse had not reached field capacity, one would not have expected leachate to accumulate above the liner and flow through the underdrain. Although 3 to 6 years may generally be required for refuse to reach field capacity (Hughes, Landon, and Farvolden, 1971), well P-12 at the base of the refuse indicated a saturated zone at least 2 feet (0.6 m) thick overlying the liner. The rapid response of the underdrain to precipitation indicates that water is able to enter and flow through the refuse. The coarse texture of the temporary cover on the landfill allows relatively rapid infiltration. The liner may retard infiltration so that a portion is diverted into the leachate collection system, but the remainder is absorbed by the refuse or percolates through the liner.

TABLE 8. Range of composition of leachate from refuse at the Crystal Lake landfill.

Parameter	Minimum mg/L[a]	Minimum meq/L[b]	Maximum mg/L	Maximum meq/L
Ca	4,000	199.6	6,200	309.4
Fe	4.2	0.15	350	12.53
Hg	.2	-	-	-
K	640	16.4	650	16.6
Mg	410	33.7	1,660	136.6
Na	1,000	43.5	1,030	44.8
Pb	0.2	-	0.4	-
Zn	34.0	1.04	46.5	1.42
Alk ($CaCO_3$)	5,589	91.6	11,800	193.4
Cl	1,020	28.8	1,602	45.2
COD	30,500	-	32,000	-
NH_4-N	-	-	-	-
NO_3-N	-	-	7.9	0.13
PH[c]	5.45	-	5.65	-
SC[c]	5,500	-	12,000	-
SO_4	-	-	992	20.7
TDS	22,750	-	22,900	-

[a] Except Hg (ppb), pH, and SC (μmhos)
[b] Milliequivalents per liter.
[c] Field measurement.

The evidence suggests that the liner may not be a highly effective barrier to the flow of leachate out of the refuse. Lysimeters installed beneath the clay liner clearly indicate the presence of contamination; however, the extremely low volumes of samples indicate a low content of soil-moisture compared to that of similar materials adjacent to the refuse.

LYSIMETER INSTALLATION AND SAMPLING RESULTS

Six lysimeters were installed in four borings beneath or adjacent to the Crystal Lake landfill. The borings were located on or near the eastern edge of filled area. Lysimeter installation data are summarized in appendix 2. Soil-moisture samples were obtained from each sampler; however, those lysimeters installed beneath the refuse (S-5, S-7) yielded consistently smaller sample volumes and occasionally produced no sample. The 25 samples obtained averaged approximately 330 mL in volume.

WATER QUALITY

Ground water

Regular analyses of chloride, iron, and total dissolved solids have been submitted to the Illinois Environmental Protection Agency since the site opened in 1973. The results of chemical analyses of water samples from the monitoring wells at Crystal Lake are included in appendix 5.

The analyses indicate that shallow ground water beneath the landfill has shown no contamination resulting from waste disposal. This might have been predicted because disposal began in 1973. At least 3 to 6 years is generally thought to be required for refuse to produce significant quantities of leachate.

The only indication of ground-water contamination at the site is found in well P-7 at the extreme north edge of the site, several hundred yards north of the landfill itself. The elevated concentrations of chloride and COD in P-7 are not the result of the landfill operations to the south, but they may reflect contamination from septic systems in the area.

The relatively high quality of ground water beneath the site is in sharp contrast to water samples from well P-12 finished in the refuse. This well was sampled on three occasions and, in each case, a black, foul-smelling leachate was obtained. The leachate was very fresh, as indicated by its low pH and high content of total dissolved solids (TDS) and COD (table 8). Clearly, this leachate would represent a significant threat to ground-water quality in the vicinity if it were allowed to migrate unattenuated from the site. This threat appears to be mitigated by several factors: (1) the relatively small volume of leachate accumulated to date, (2) the silty nature and comparatively low permeability of the underlying materials, and (3) the thickness of unsaturated, calcareous silty sand beneath the refuse, which probably represents a significant buffer zone.

TABLE 9. Range of composition of soil-moisture samples from lysimeters at the Crystal Lake landfill.

	Uncontaminated				Contaminated			
	Minimum		Maximum		Minimum		Maximum	
	(mg/L)[a]	(meq/L)[b]	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Ca	96	4.79	776	38.72	99	4.94	1,720	85.83
Fe	0.0	0.00	0.15	0.01	0.65	0.02	85.0	3.04
Hg	<0.2	-	< 0.2	-	<0.2	-	<0.2	-
K	0.5	0.01	2.8	0.07	6.0	0.15	46.0	1.18
Mg	19	1.56	55	4.52	20	1.64	93	7.65
Na	6.5	0.28	22.0	0.96	9	0.39	220	9.57
Pb	< .01	-	< .01	-	< .01	-	< .01	-
Zn	0.03	0.001	0.17	0.005	0.04	0.001	0.24	0.007
Alk ($CaCO_3$)[c]	200	3.28	581	9.52	344	5.64	960	157.3
Cl	16	0.45	31	0.88	39	1.10	750	21.16
COD	5	-	17	-	27	-	440	-
NH_4-N	0.0	-	0.0	-	0.0	0.00	13.0	0.72
NO_3-N	0.3	0.005	4.7	0.076	1.0	0.02	38.0	0.61
pH[c]	6.35	-	7.14	-	6.35	-	7.40	-
SC[c]	700	-	1,100	-	850	-	3,400	-
SO_4	73	1.52	130	2.71	64	1.33	250	5.21
TDS	619	-	838	-	795	-	3,664	-

[a] Except Hg (ppb), pH, and SC (μmhos).
[b] Milliequivalents per liter.
[c] Field measurement.

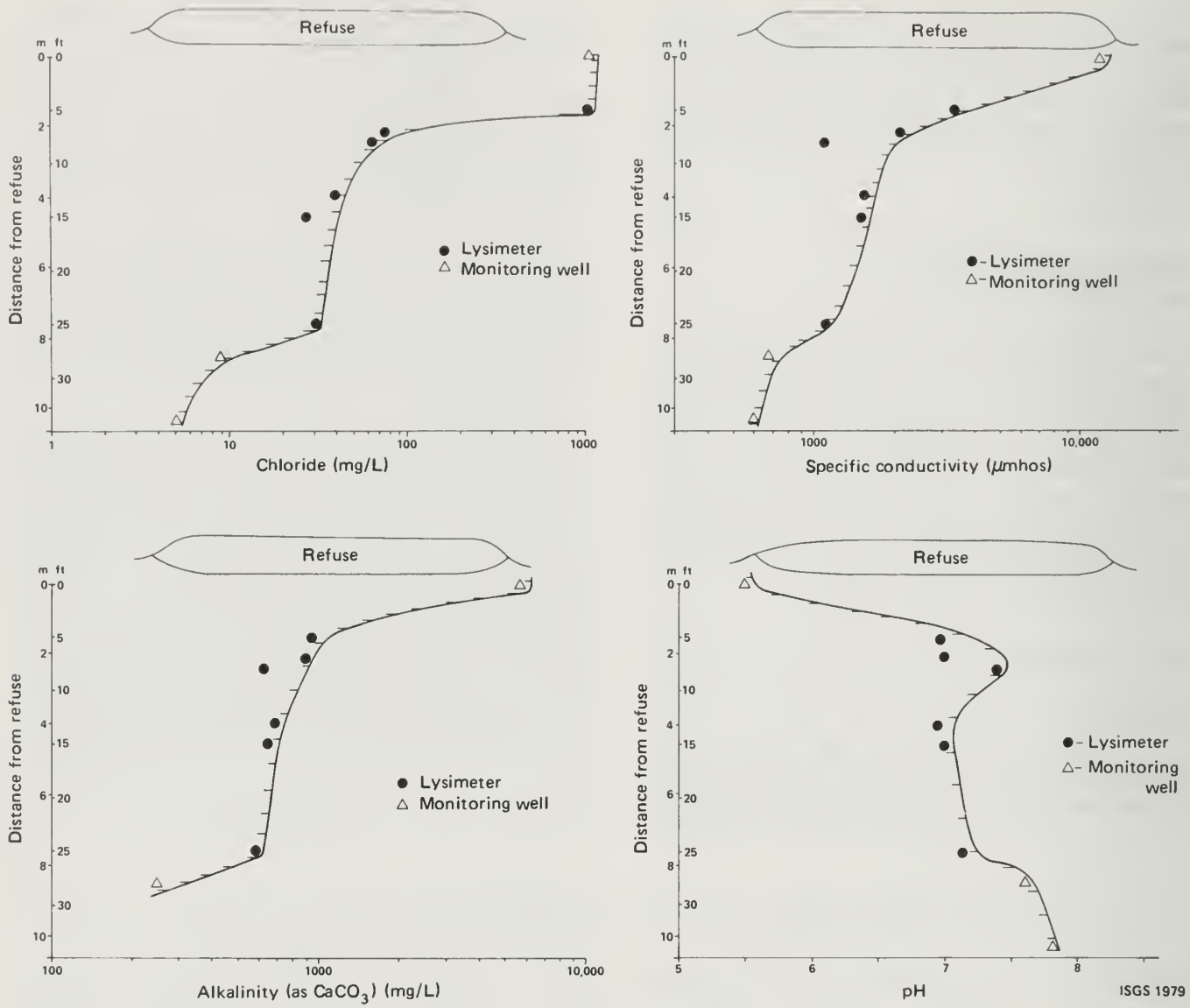


Figure 22. Concentrations of selected parameters as a function of distance from the refuse in water beneath the Crystal Lake landfill on August 22, 1977. The hachured line represents the maximum concentration observed at that particular depth. The concentration at a distance of 0 feet represents leachate samples from well P-12 in the refuse.

Soil moisture

The results of chemical analyses of samples of soil moisture from lysimeters at Crystal Lake are included in appendix 4. Between June 23, 1976, and August 22, 1977, 23 water samples for chemical analysis were obtained. The range in composition of contaminated and uncontaminated soil moisture samples is shown in table 9, both in absolute (mg/L) and relative (meq/L) concentrations. This table should be compared with table 8 which shows the range in quality of leachate samples obtained from well P-12, which is finished in the refuse.

The order of maximum relative concentrations in contaminated soil moisture was generally: Alkalinity >> Ca >> Cl > Na > Mg > SO_4 > Fe > K > NH_3 > NO_3. The pH of contaminated soil moisture ranged from 6.35 to 7.40. Raw leachate from the refuse, however, had the following order of relative concentrations: Ca >> Alka-linity > Mg > Cl > Na > SO_4 > K > Fe > Zn, and had a pH of approximately 5.50. Uncontaminated soil moisture, on the other hand, had minimum relative concentrations in the decreasing order: Ca > Alkalinity > Mg = SO_4 > Cl >> K, and a pH range of 6.35 to 7.14.

Samples from some lysimeters clearly show contamination of soil moisture by leachate, although other lysimeters reflect the background quality of soil moisture resulting from infiltration. The two lysimeters installed beneath the refuse and liner, S-5-SL-1 and S-7-SL-1, sample soil moisture that migrates out of the landfill through the liner and moisture that might flow toward the lysimeter from adjacent or underlying materials.

The remaining four lysimeters in borings S-3 and S-4

are situated adjacent to the east edge of the landfill. Soil moisture from these lysimeters appears to indicate the lateral migration of leachate which was observed at the Savanna landfill. Because of the coarse texture of the overlying materials, the quality of soil moisture adjacent to the landfill is also influenced by direct infiltration.

Effect of distance from refuse on soil moisture quality. Figure 22 describes the quality of leachate, soil moisture, and ground water beneath or adjacent to the landfill on August 22, 1977. A generalized cross-section of the landfill is included in each diagram and the hachured line indicates the maximum concentration of each parameter at that particular depth. The concentration of each parameter except pH is plotted on a logarithmic scale versus distance from the refuse. On each diagram, the concentration at a depth of 0 feet represents samples of raw leachate from well P-12.

The diagrams appear to show significant attenuation of leachate taking place beneath the refuse. The concentrations of most constituents in the raw leachate were generally ten times greater than in soil moisture at a depth of 5 feet (1.5 m) below the refuse. The exception is chloride, which is among the most mobile inorganic species and is readily leached from refuse. Chloride concentrations beneath the refuse fluctuated greatly; however, the sample from S-7-SL-1 collected August 22, 1977, contained nearly as much chloride as the raw leachate. The dramatic decreases in specific conductivity and alkalinity with distance from the refuse indicate that significant reductions in the concentrations of certain ions occurred during migration. Soil moisture from lysimeter at a depth of 6.6 feet (2.0 m) beneath the refuse (S-5-SL-1) was not as contaminated as that from S-7-SL-1; this may reflect the variability of leachate quality or liner conditions near the eastern edge of the landfill.

Samples from the lysimeters in S-3 and S-4 showed gradual decreases in the concentrations of most parameters with depth, this may reflect the migration and resulting attenuation of soil moisture affected by leachate. The contamination may have resulted from two possible sources. The steep slopes of the landfill promote surface water runoff, and lysimeters adjacent to the landfill may intercept infiltration from contaminated surface water. Surface runoff observed during this study, however, did not appear to be contaminated as it generally was not in contact with refuse. The contamination indicated by lysimeters adjacent to the refuse may also originate from the migration of leachate laterally away from the refuse. Chemical analyses indicated gradual decreases in the concentrations of most ions in soil moisture to a distance of 26 feet (8 m) from the refuse. Ground water, however, was generally less mineralized and has a higher pH (fig. 22) than the soil moisture immediately above. Whether this difference is due to contamination of soil moisture or whether it represents normal soil-moisture quality resulting from migration through the unsaturated zone is not known.

The shallowest lysimeter in S-3-SL-3, at a distance of 7 feet (2.2 m) from the refuse, clearly shows the results of contamination by iron, chloride, COD, and sodium, as well as total dissolved solids and several other parameters. Moisture from S-3-SL-2, at a distance of 13 feet (4 m), however, is generally less contaminated, although levels of some parameters such as chloride, sodium, sulfate, and calcium are still high. At a distance of 25 feet (7.6 m), soil moisture appears to be essentially uncontaminated although, as noted previously, concentrations of many parameters are measurably greater in soil moisture than in uncontaminated ground water.

Variation in quality of soil moisture with time and distance from refuse. The quality of samples collected between June 23, 1976, and August 22, 1977, is illustrated in figure 23, which shows changes in concentration of selected parameters with time in soil moisture samples. Samples were collected at intervals of 67 to 210 days beginning approximately two and a half years after initial refuse disposal. It was anticipated that the migration of leachate from the refuse following the attainment of field capacity could be monitored by lysimeters beneath and adjacent to the landfill. No long-term increases in the concentrations of the constituents with time were observed, although short-term fluctuations were abundant. These figures also indicate the effects of distance from the refuse on soil moisture quality.

The four lysimeters adjacent to the refuse at depths below the surface of 9 feet (2.7 m) to 37 feet (11.3 m) showed similar trends in the concentrations of calcium, chloride, COD, and total dissolved solids, and partial trends in levels of iron and sulfate. Some ions, such as potassium and sodium, fluctuated widely with depth and time. Samples from the lysimeters beneath the refuse (S-5 and S-7), on the other hand, were much more highly contaminated with the exception of potassium, sulfate, and nitrate. The trends of chloride and especially TDS in S-5 and S-7 with time are somewhat similar to that of the other lysimeters.

The reasons for the changes in calcium concentrations with time are not clear, although the fluctuations have been remarkably uniform in samples from lysimeters in S-3 and S-4. The changes may reflect responses to precipitation or possibly the results of ion-exchange reactions of leachate with calcareous soils.

Many of the diagrams illustrate the effects of infiltration and leachate migration with depth. The lysimeters beneath the refuse reflected a nearly identical increase in COD from March to August 1977, although those adjacent to the landfill showed a general decline in COD over the same period. Distance from the landfill accentuates the processes of attenuation; dilution from infiltration, dispersion, and more oxidizing conditions reduce the effects

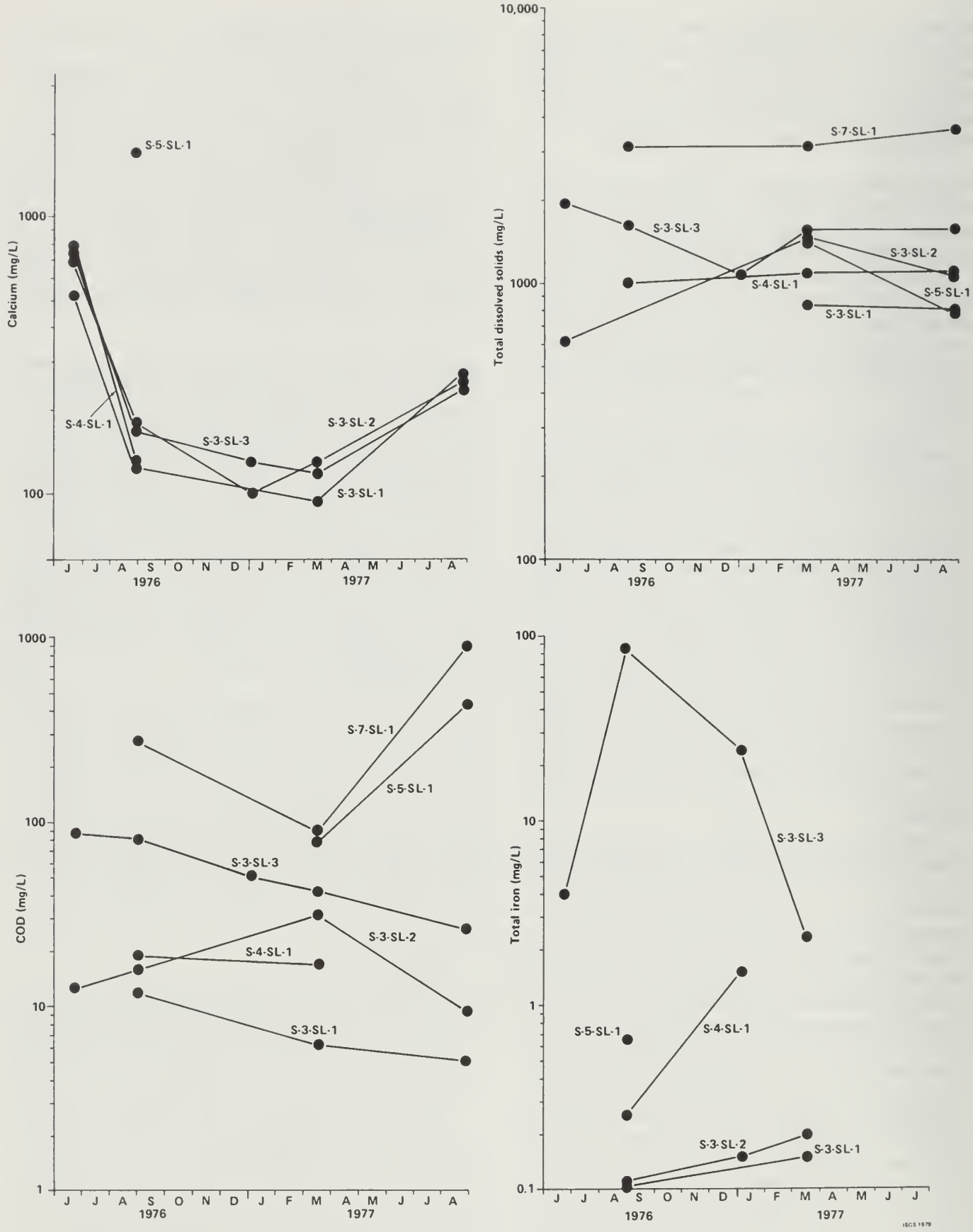
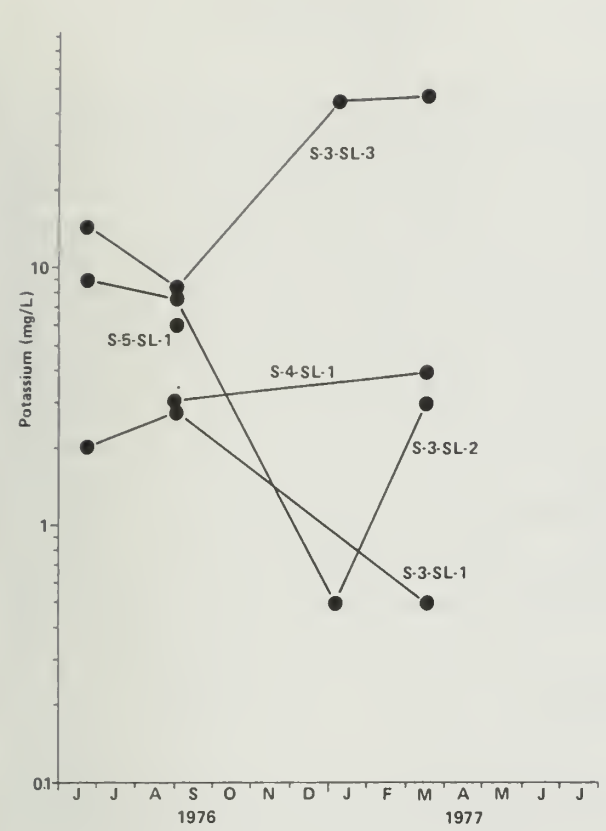
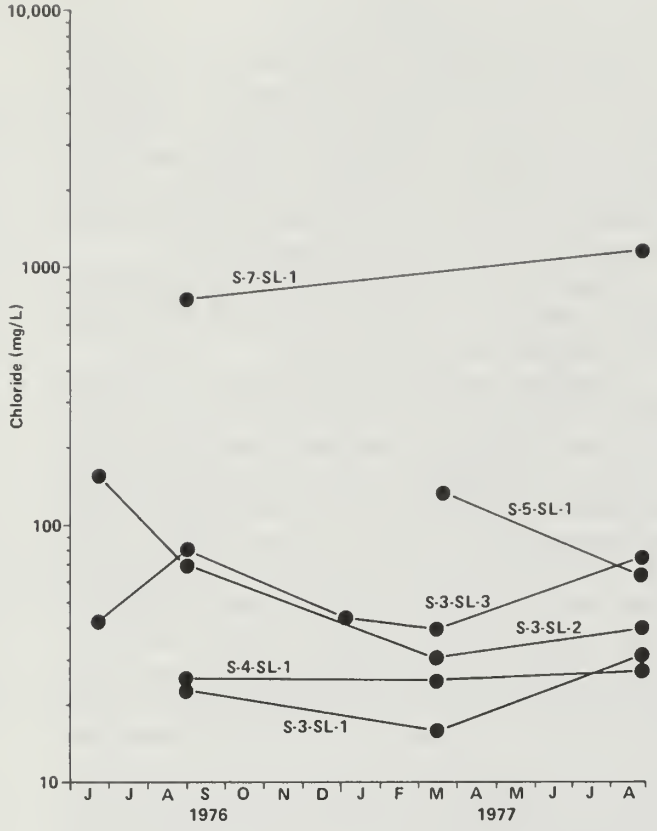
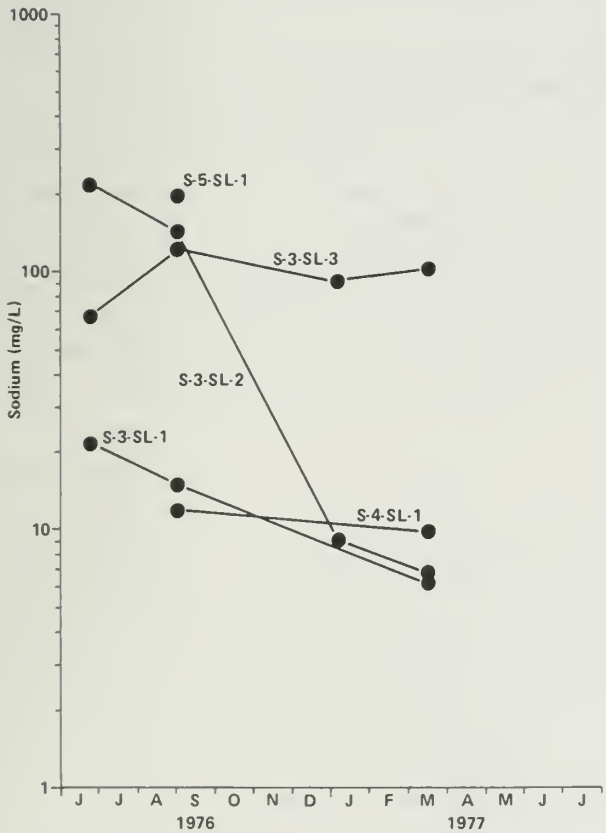


Figure 23. Changes in concentrations of selected parameters with time in soil moisture from lysimeters at the Crystal Lake landfill. S-7-SL-1 represents suction lysimter number 1 in boring S-7.







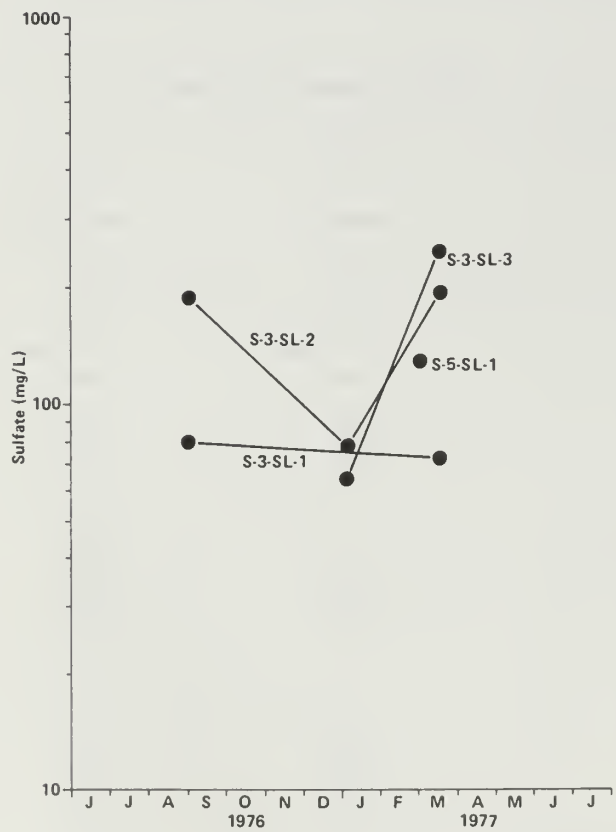


Figure 23. *(continued)*

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of contamination by leachate.

Generally, the quality of soil moisture improves with depth in S-3. Samples from the shallowest lysimeter (SL-3) are consistently more contaminated than those from SL-2, and those from SL-1 are usually the least affected. Occasionally samples from SL-3 showed an increase or decrease in parameter, such as iron or sodium, but samples from deeper lysimeters did not respond similarly.

No lead or mercury was detected in any soil-moisture samples. Levels of zinc, which were not high, were variable with time and distance from the refuse.

The relatively coarse, permeable nature of the materials adjacent to the landfill has probably limited the effects of the lateral migration of leachate. Attenuation processes have reduced chloride concentrations by approximately 95 to 98 percent at a distance of approximately 10 feet (3 m) from 4-year-old refuse; however, beneath the refuse at a depth of 5 feet (1.5 m), chloride concentrations have been reduced by only 10 percent of that in raw leachate. This level of contamination may not be present beneath the entire landfill. The liner and leachate collection system should limit leakage; however, the heterogeneity of the clay liner may also result in small areas of leachate penetration beneath the fill. It should be noted that a sample of soil moisture from S-5-SL-1 at a depth of 6.6 feet (2.0 m) beneath the refuse, east of S-7, contained concentrations of chloride 95 percent less than that found in raw leachate.

SUMMARY

The typical composition of raw leachate, contaminated and uncontaminated soil moisture, and ground water at the Crystal Lake landfill is illustrated in table 10. As at the other two sites, uncontaminated soil moisture and ground water are quite similar in composition. In general, soil moisture has a lower pH than ground water and, at Crystal Lake, soil moisture contains slightly more calcium, chloride, and total dissolved solids. Raw leachate was collected from monitoring well P-12 finished in the refuse over the clay liner. Except for heavy metals, this leachate was very highly contaminated, as expected for refuse approximately three years old. Contaminated soil moisture collected from lysimeter S-7-SL-1, 3 feet (1 m) below the liner and approximately 5 feet (1.5 m) below the refuse, appears to indicate the degree of attenuation currently resulting from migration through the liner. Concentrations of virtually every parameter are greatly reduced at this depth. The exception is chloride, which is present in the soil moisture beneath the liner at levels comparable with raw leachate.

The relative distribution of major cations (fig. 24) illustrates a distinct difference between uncontaminated soil moisture and ground water. Soil moisture contains relatively more calcium and less magnesium than ground water. The effects of contamination by leachate are reflected by the

TABLE 10. Composition of leachate, soil moisture, and ground water at the Crystal Lake landfill.

	P-12 Leachate (mg/L)[a]	S-7 Contaminated soil moisture (mg/L)	Uncontaminated soil moisture (mg/L)	P-8 Ground water (P-8) (mg/L)
Ca	6,200	1,720	96	47
Fe	350	85	0.0	0.4
Hg	< .2 ppb	< .2 ppb	< .2 ppb	<0.2 ppb
K	650	46	0.5	0.5
Mg	1,660	93	19	19
Na	1,030	220	7	2
Pb	0.4	< .01	< .01	< .01
Zn	46.5	0.24	0.03	0.6
Alk ($CaCO_3$)[b]	11,800	960	200	240
Cl	1,602	750	16	6
COD	32,000	440	5	4
NH_4-N	-	13	0.0	-
NO_3-N	7.9	38	0.3	3.9
pH[b]	5.65	7.40	6.35	7.48
SC[b]	12,000	3,400	700	520
SO_4	992	250	73	40
TDS	22,900	3,664	619	400

[a] Except Hg (ppb), pH, and SC (μmhos).
[b] Field measurement.

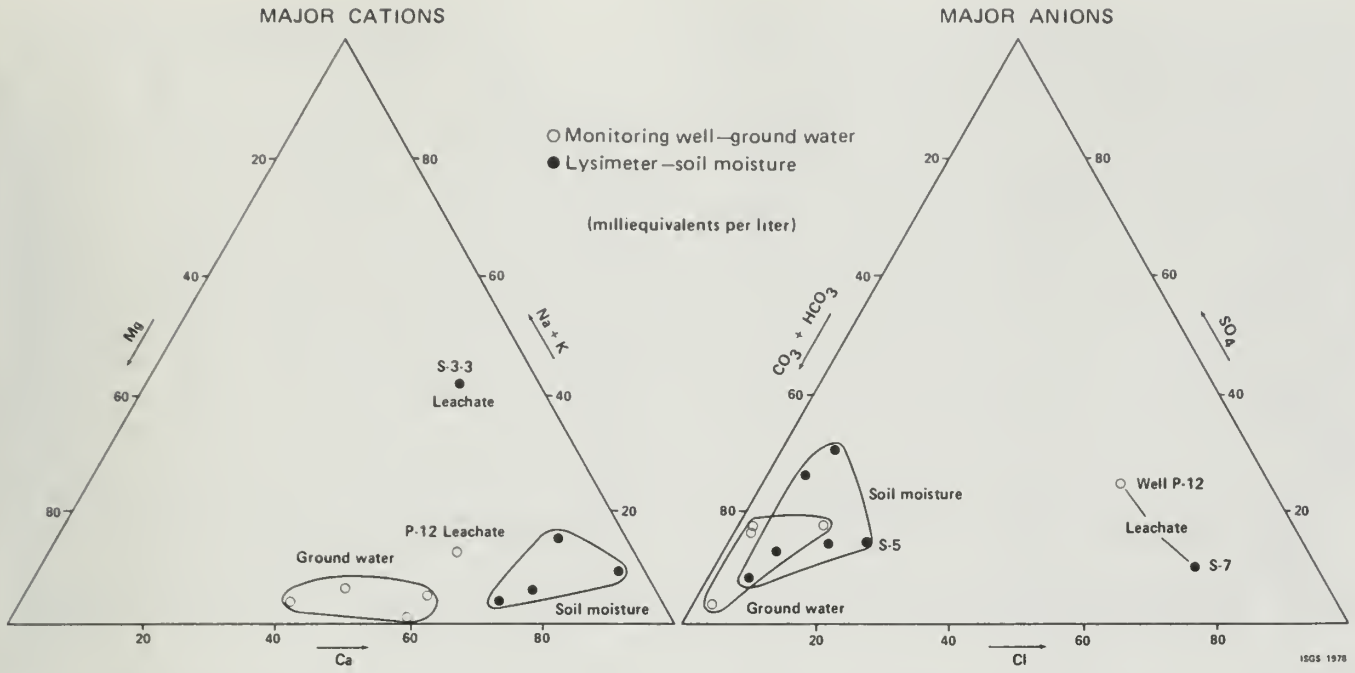

Figure 24. Distribution of major cations and anions in soil moisture and ground water at the Crystal Lake landfill. Results are in milliequivalents per liter.

greater percentage of sodium plus potassium in S-3-SL-3. Raw leachate, represented by P-12, however, has a distribution more similar to that of uncontaminated samples.

Soil moisture and ground water are both high in bicarbonate (as alkalinity) and low in chloride and sulfate (fig. 24). Leachate, on the other hand, illustrated by well P-12 and S-7, contains a relatively high percentage of chloride. Both lysimeter S-5 and lysimeter S-7 collect soil moisture from beneath the refuse and liner; however, samples from S-5 are relatively uncontaminated and samples from S-7 are highly contaminated. Lysimeter S-5 is situated closer to the east edge of the landfill and is approximately 1.6 feet (0.5 m) deeper than S-7. Leakage of leachate through the liner near S-7 may be responsible for local contamination, but samples from lysimeter S-5 appear to represent background soil moisture quality.

SOIL CHEMISTRY

The Crystal Lake landfill is underlain predominantly by outwash deposits of uniform sand, silty sand, and sandy silt. Formerly the site was overlain by a thin succession of sand and gravel and sandy glacial till. Mining operations thoroughly mixed the sandy, gravelly Haeger Till with the clayey topsoil developed on its upper surface. This combination of till and topsoil material was used as a liner at the base of the refuse overlying coarser deposits of silty, sandy outwash. Table 7 illustrates the general texture, clay mineralogy, and cation exchange capacity of each of these materials.

The analyses indicate that the silty and sandy materials beneath the liner have a very limited capacity for the attenuation of leachate, as CEC values average only 1.05 meq/100 g of soil for six samples. The clay liner placed beneath the refuse basically consists of two parts: (1) a thin (0.4 in. [1 cm]) layer of bentonite clay spread over the underlying sandy material and (2) 2 feet (0.6 m) of compacted glacial till placed over the layer of bentonite (fig. 18). The glacial till includes a mixture of clayey topsoil material originally developed in the till. The liner was sampled at two locations (S-5 and S-7), and nine samples of the liner and underlying materials were submitted for chemical analyses. The results are included in appendix 3 and are presented graphically in figure 25. The data indicate that the liner has considerably greater cation exchange capacity (2.5 to 4.5 meq/100 g) than the underlying materials, but that the actual values of CEC are not very large. Samples of the liner consisted of the compacted glacial till-soil mixture and did not include any of the thin seam of bentonite clay immediately below. Data supplied by American Colloid, Inc., the makers of Volclay (Hughes, 1975), indicate that the bentonite, which consists mainly of the sodium-saturated clay mineral montmorillonite, is designed to swell from 10 to 15 times its original volume upon contact with water. CEC values of 80 to 150 meq/100 g are generally associated with montmorillonite; however, the limited amount of bentonite used beneath the site and the method of application appear to limit its potential for significant attenuation of leachate. The attenuation capabilities of the liner probably depend more on the exchange capacity and integrity of the compacted layer of glacial till. The underlying thin layer of

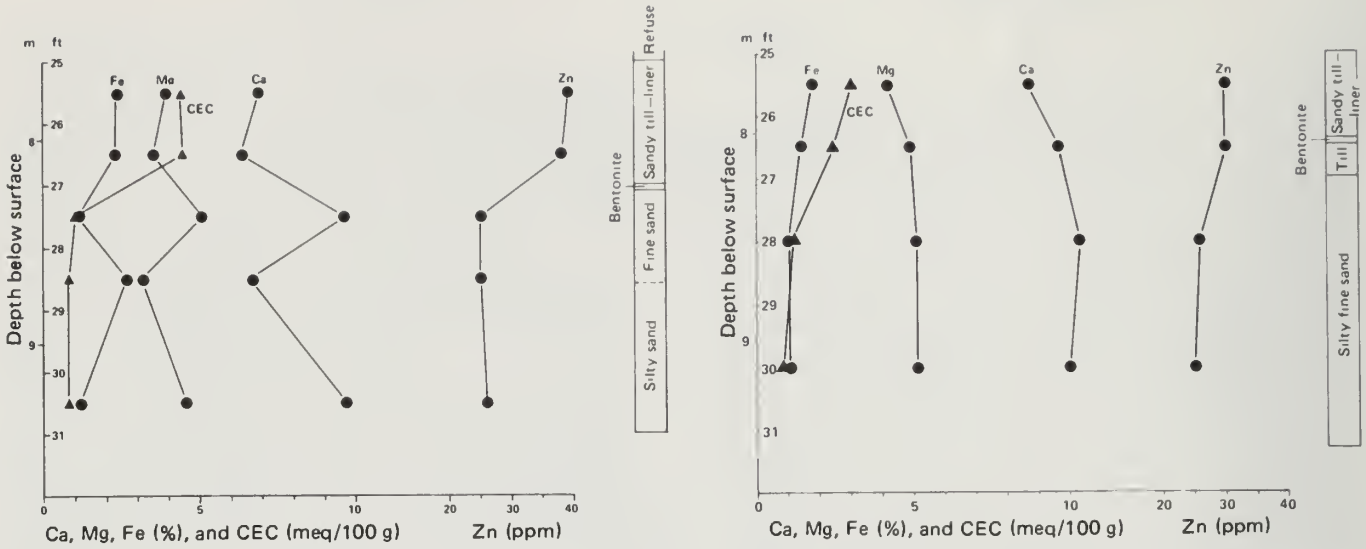

Figure 25. Chemical analyses of soil samples of the liner and underlying materials from lysimeter borings S-7 (left) and S-5 (right) beneath the Crystal Lake landfill.

bentonite provides for additional adsorption of contaminants and has limited permeability (provided the seam is reasonably intact) affecting the leachate that has pentrated the overlying glacial till.

The attenuation capacity of geologic materials depends on the concentration of ions in the leachate as well as the exchange characteristics of the medium. The range of soil-moisture quality at the Crystal Lake landfill is shown in table 9. Relative (meq/L) and absolute (mg/L) concentrations of most ions indicate the character of contaminated and uncontaminated soil moisture. The composition of leachate in contact with the liner is shown in table 8. This represents the quality of leachate in contact with the liner.

Figure 25 illustrates the sequence of materials encountered in borings S-7 and S-5, the concentrations of several cations, and the CEC of soil samples from each unit. As at Geneseo and Savanna, lead and sulfate were not present above limits of detection. The samples were not analyzed for mercury. The pH of a sample of till from the liner in boring S-5 was 7.6; two samples of the underlying sandy silt had a pH of 8.7.

Concentrations of calcium and magnesium were generally higher in the underlying silty sand than in the liner. All soil samples from this site submitted for chemical analysis were calcareous, although some leached topsoil material may have been included in the liner. Some calcium and magnesium may have been removed from the liner as a result of interaction by leachate. The changes in calcium and magnesium concentrations with depth are distinctly parallel, suggesting similar chemical behavior.

The iron content of the glacial till liner in S-5 was distinctly greater than the underlying sand. S-7 shows a similar trend except for a sample of oxidized sand, at a depth of 28.5 feet (8.7 m), that had the highest iron content of any sample, 2.66 percent. Samples from the till liner averaged 2.00 percent of iron, but underlying deposits of sand contained only 1.13 percent of iron. This difference may have been the result of a greater percentage of iron oxides originally present in the mixture of till and topsoil. Precipitation of iron from the leachate also may have been responsible, as indicated by the slight, but noticeable increase in iron content in the upper portion of the liner.

Concentrations of zinc, although much less than iron, also decreased with depth in S-5 and S-7. The zinc content of the sands beneath the liner was consistent, averaging 25.5 ppm; samples of the till-soil liner averaged 34.1 ppm. Zinc is probably associated with iron oxides and percentage of clay; this is due to ion exchange or adsorption on clays and the tendency to co-precipitate with iron-oxide compounds.

The potassium content of the soil samples did not reflect any consistent trends. Samples from S-5 showed a slight increase in potassium with depth. Concentrations of sodium and chloride showed no evidence of contamination.

Although there are significant differences between the chemical composition of the till-soil liner and the underlying fine sand, it is questionable whether these are the result of contamination by leachate or whether they are due to differences in the original composition of the materials. There appeared to be little difference between the composition of fine sand samples from immediately beneath the liner and similar, though uncontaminated, samples from borings P-6 and P-11. To adequately determine the effects of leachate on soil beneath the landfill would require the analysis of samples obtained prior to refuse emplacement and similar samples taken at later times.

EVALUATION OF DATA ON QUALITY OF SOIL MOISTURE AND GROUND WATER

The chemical analyses of samples of soil moisture collected with pressure-vacuum lysimeters provided information regarding the extent of leachate contamination beneath each landfill studied. The migration of contaminants through unsaturated soils and the resulting attenuation was monitored with simple, repeated sampling of soil moisture. The range of concentrations of leachate components in soil-moisture samples from all lysimeters at the Geneseo, Savanna, and Crystal Lake landfills is shown in table 11. In addition to the relatively mobile contaminants such as Cl, SO_4, and Ca, other constituents including several trace elements (such as Fe, Zn, and Mg), COD, and pH were detected and used to describe the quality of soil moisture in the vicinity of each lysimeter. Table 11 also shows that presure-vacuum lysimeters are able to sample a wide range of water quality. Although measured concentrations of heavy metals such as Hg and Pb were negligible in soil moisture, this was probably not the result of screening by the sampler. Raw leachate obtained from wells finished in the refuse at these sites also contained virtually no Pb or Hg.

A summary of the relative distribution of major cations in soil moisture and ground water from all three landfills (fig. 26) illustrates a distinct difference between samples of uncontaminated ground water and uncontaminated soil moisture. Soil moisture, in general, contained relatively

TABLE 11. Range of concentrations of leachate components in soil-moisture samples from all lysimeters at the Geneseo, Savanna, and Crystal Lake landfills.

	Minimum (mg/L)[a]	Maximum (mg/L)
Ca	53	5,600[b]
Fe	0.0	450[b]
Hg	< 0.2	<0.2
K	0.4	46.0
Mg	7	900[b]
Na	5	1,260
Pb	< .01	0.10[b]
Zn	< .01	0.90[b]
Alk ($CaCO_3$)[c]	175	9,410
Cl	15	3,583
COD	4	8,898
NH_4-N	0.0	240[b]
NO_3-N	< 0.1	172
pH[c]	6.05	7.05
SC[c]	525	7,000
SO_4	< .01	250
TDS	537	10,186

[a] Concentrations in mg/L except Hg (ppb), pH, and SC (μmhos).
[b] Leachate samples from refuse at the Savanna landfill.
[c] Field measurement.

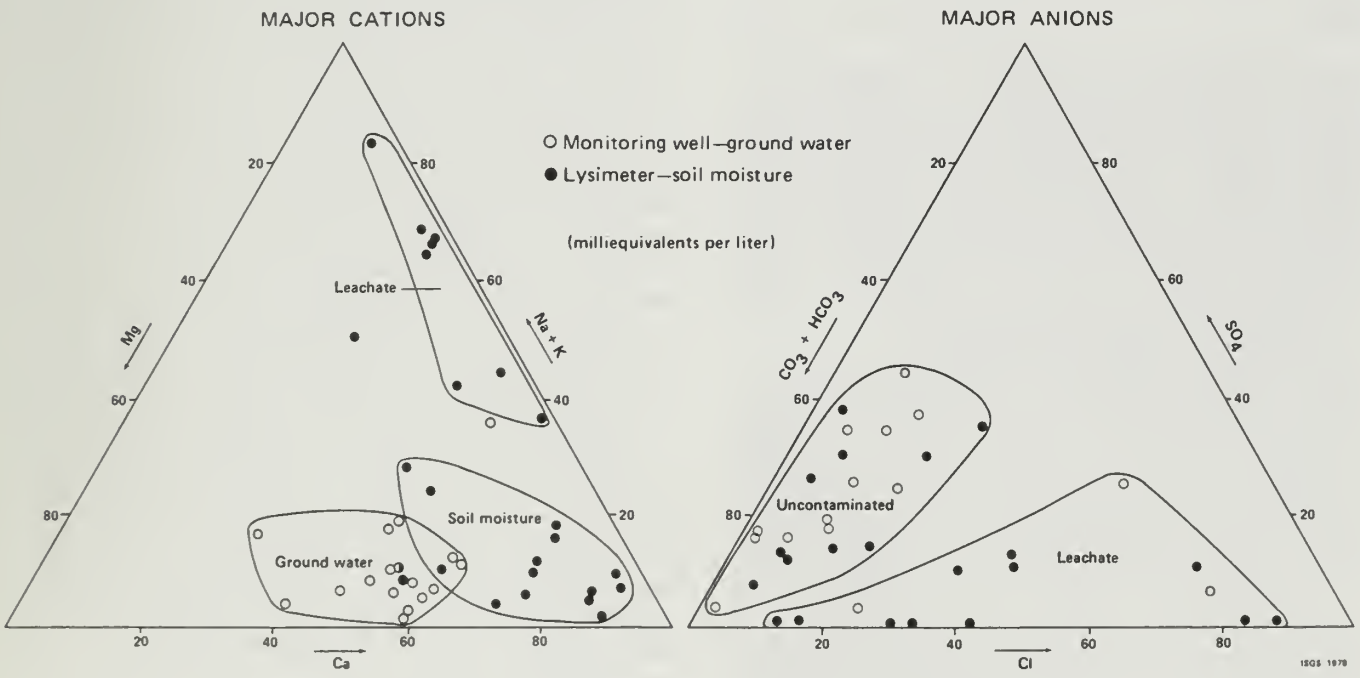

Figure 26. Distribution of major cations and anions in soil moisture and ground water at the Geneseo, Savanna, and Crystal Lake landfills. Results are in milliequivalents per liter.

more calcium and less magnesium than ground water. Samples of leachate, however, were represented almost entirely by soil-moisture samples from the lysimeters. The greater relative content of Na + K in soil moisture contaminated by leachate produces a distinctly different composition on the triangular diagram of cations in figure 25.

The distribution of major anions in soil moisture and ground water from all three landfills (fig. 26) is similar to that of cations, although on this diagram the composition of anions in uncontaminated ground water and soil moisture has relatively wide but similar range. Samples contaminated by leachate also have a wide range in relative compositions; however, the greater content of Cl and depletion of SO_4 in contaminated samples makes their relative composition quite distinct from that of uncontaminated samples.

Although a few shallow wells, including those finished in refuse, showed signs of leachate contamination, the majority of the monitoring wells at these landfills have not been affected by leachate. Contamination by leachate was detected almost solely by samples of soil moisture. Given enough time and more crucial placement of monitoring wells at these three landfills, contamination of ground water probably will be observed. The extent and consequences of this contamination will depend on the fluxes and attenuation of pollutants in both the unsaturated and saturated zones beneath each site.

EVALUATION OF MONITORING TECHNIQUES

Methods

The techniques used in this study for monitoring the migration of leachate from landfills included monitoring wells to sample the ground water in the saturated zone, chemical analysis of soil samples, and sampling of soil moisture in the unsaturated zone. Monitoring-well techniques and their limitations are described elsewhere in the literature (Everett et al., 1976; and Fenn et al., 1977). As discussed previously, wells are generally not suited for evaluating flow in the unsaturated zone.

Soil samples collected during installation of the lysimeters and monitoring wells were submitted for chemical analysis to determine the effects of leachate migration. The results are included in appendix 3. These data, however, reflect the chemical character of the sediments at the particular time the samples were taken. Subsequent borings would be required to define changes in soil chemistry with time. This process is both expensive and time consuming.

Pressure-vacuum lysimeters have the advantage of providing soil-water samples repeatedly if adequate soil moisture is present. By the time ground-water pollution is observed in monitoring wells, it may have progressed to the point where corrective procudures are very difficult and expensive. The advantages of using soil-moisture samplers for monitoring water quality in the unsaturated zone are evident; indications of severe imminent contamination are available prior to the introduction and spread of pollutants in ground water beneath waste disposal sites.

Installation and operation of lysimeters

Lysimeters can be installed rapidly and inexpensively if continuous soil sampling is not required during drilling. Multiple lysimeters can be installed in individual borings in a single day using solid-stem augers and, where possible, even a hand auger. If continuous soil sampling is also desired, the installation of lysimeters is more time consuming. By placing lysimeters in the unsaturated zone, however, many problems normally associated with the installation of monitoring wells, such as caving boreholes, are avoided.

Lysimeters were successful in monitoring soil-moisture conditions with only a few exceptions. Initially, some lysimeters at Savanna would not yield water samples. After allowing sufficient time (generally a few weeks) for soil-moisture conditions to reach equilibrium with the ceramic cup and surrounding silica sand, virtually every lysimeter at Savanna provided soil-moisture samples. Additional problems arose during cold weather as moisture froze in the access tubes on several occasions and prevented sampling.

Factors affecting performance of lysimeters

Effects of infiltration, refuse, and liners. Crucial to lysimeter performance are those factors controlling infiltration and soil moisture into and through both refuse and the underlying geologic materials. Studies of landfills in northern Illinois (Hughes, Landon, and Farvolden, 1971) have shown that even with ideal refuse compaction and cover materials, one-third of the annual precipitation may infiltrate the surface of the landfill. Initially, most of this infiltration is absorbed by refuse and interbedded intermediate cover materials and little will migrate out of the bottom of the landfill. Estimates of the time before significant quantities of leachate are continuously generated by a landfill in a humid climate range from 2 to 6 years (Hughes, Landon, and Farvolden, 1971). Leachate, however, was observed immediately following refuse burial in samples of soil moisture from a lysimeter installed prior to waste disposal at Savanna. This may have been moisture originally present in the waste which was squeezed out during burial and compaction or, more likely, it may have been the result of channeling of infiltration through the refuse and into the underlying materials. Channeling may also be responsible for the discharge of apparently uncontaminated water from the underdrain at the Crystal Lake landfill during rainfall.

Related to the effects of refuse and cover emplacement is the impact of an artificial clay liner such as that installed at Crystal Lake. A properly installed clay line should

restrict the migration of leachate from a landfill.

Geologic materials. The geologic environment of each landfill site affects both the volume and quality of soil-moisture samples collected by lysimeters. The type of soil governs the rate of movement and the chemistry of ground water and soil moisture including the degree of attenuation of contaminants.

Sandy soils allow relatively rapid movement of water under conditions of near saturation, but they generally have a much lower natural water content than fine-grained soils at the same soil-water pressure (tension). Lysimeters placed in different materials will reflect the moisture conditions in each particular soil. In general, a vacuum applied to a lysimeter will pull soil moisture from the surrounding soils to the ceramic tip until the tension of moisture remaining in the soil is equal to that applied by the lysimeter.

If adequate soil moisture is present (near saturation), it is relatively easy to induce the flow of water from a sandy soil into a lysimeter. Sample volumes decline considerably if soil moisture is depleted in the vicinity of the lysimeter because of a lack of recharge. On the other hand, moisture fronts from individual precipitation events moving through sandy soils may provide enough water to fill the lysimeter. In this case, the water sample will represent a single rainfall-infiltration event and not background soil moisture conditions.

Lysimeters placed in fine-grained glacial till or silt may yield smaller sample volumes than those in sand. Although water content is frequently high in fine-grained soils, the low hydraulic conductivity limits the volume of water that will move into a lysimeter over a given time.

Zones of low permeability may occasionally provide better conditions for lysimeters. A layer of glacial till or fine-grained silt that overlies coarse-grained, unsaturated sand or sand and gravel will generally have a water content greater than that which would be expected if no coarse-grained layer were present. The water content of the fine-grained unit may reach saturation before water moves into the coarse-grained material below. This phenomenon has been observed and demonstrated by several workers (Corey and Horton, 1969; Palmquist and Johnson, 1962; Clothier, Scotter, and Kerr, 1977; and Hillel and Talpaz, 1977) and results because the natural water content for a given soil-moisture tension is much lower in the sand than in the overlying finer-grained materials. In order for water to flow into the coarse-grained, more permeable material below, the soil-moisture pressure must increase (decreasing tension) until adequate soil moisture is present between the grains of the coarser unit. At this pressure, however, the water content of the overlying fine-grained material will have become nearly saturated. Once saturated, water will flow into the underlying sand, and it will continue to flow as long as the soil-moisture pressure is nearly atmospheric in the overlying material. If there is a reduction in infiltration, little moisture may flow from the fine-grained material into the underlying sand. Thus, there may be very little soil moisture in the sand available to a lysimeter; whereas, in the overlying fine-grained material, where abnormally high-water content may exist, a lysimeter may operate quite well.

Miscellaneous factors. Although pressure-vacuum lysimeters have been designed to operate in the unsaturated zone, it appears that they also may provide a unique method for sampling zones of temporary saturation, frequently called perched ground water. A monitoring well placed in a zone of temporarily perched ground water would require very carefully timed sampling to obtain water samples; whereas, a lysimeter installed in this zone can continually provide water samples at different times and states of saturation.

Many other factors affect the performance of a lysimeter. For example, in similar materials the natural water content generally increases with depth toward the water table. If there are relatively constant geologic conditions and infiltration, greater volumes of soil moisture would be expected from lysimeters that are deeper and nearer the water table.

Geologic units must be carefully described during the installation of lysimeters. In order to evaluate the performance of lysimeters and the actual rates of contaminant movement, it is essential to know the specific geologic framework of each site.

CONTROL OF LEACHATE IN UNSATURATED SOILS

The implications of waste disposal and leachate control in unsaturated materials have only recently become of concern to practicing hydrogeologists. Whereas the factors that control saturated ground-water flow are reasonably well known to geologists and engineers, the laws governing unsaturated flow are commonly misunderstood and misapplied. The unsaturated component of the ground-water flow system is neglected in most hydrogeologic studies.

A frequently encountered hypothesis states that leachate will not form or migrate from solid waste emplaced above the zone of saturation. This study and others by Apgar and Langmuir (1971), Hughes, Landon, and Farvolden (1971), and Gerhardt (1977), however, show that infiltration will result in leachate migration through unsaturated materials beneath waste disposal sites in humid climates. Although this zone of partial saturation is generally a good buffer zone, the monitoring and control of leachate can be a difficult proposition. Whereas relatively simple techniques, such as using wells, commonly can be used to remove and renovate contaminated ground water in saturated materials, such methods are generally not applicable to cases of extensive soil-moisture contamination indicative of imminent ground-water pollution. Where the underlying unsaturated

materials are thick, correcting the migration of the hazardous pollutant can be more involved and costly and usually is detected later than at sites nearer or below the water table. If the surrounding soils are sufficiently fine grained to provide adequate renovative capabilities, disposal above the water table would be of limited concern; however, those areas which have a well-defined, deep water table are generally underlain by coarse-grained materials that drain ground water and, potentially, leachate from the site.

Landfill liners and leachate collection systems also are generally designed for use in a saturated system where ground-water flow through fine-grained materials is restricted and water easily flows into a gravel drain from which it can be pumped for treatment. In unsaturated soils, however, infiltration may actually bypass a leachate collection system, especially if the collection system consists of a narrow, coarse-gravel drain overlying a wide liner with a low hydraulic conductivity. In partially saturated soils, water is held under tension in progressively smaller pores; as water contents decrease, tension increases. Thus, the large pores of a gravel drain are the first to be drained with partial dewatering and the last to be filled upon rewetting. Hydraulic conductivity also decreases with a reduction in saturation to the point where it approaches zero in the absence of water-filled pores.

Infiltration through the surface of the landfill will raise the water content of the cover and refuse; however, saturation is not required for downward movement toward the water table. In partially saturated soils, soil moisture may move preferentially through fine-grained materials whose predominantly small pores remain filled with water. An adjacent gravel drain, on the other hand, contains few large pores that require nearly total saturation before soil moisture will enter. In unsaturated materials, therefore, a sump or gravel drain may be dry, but flow may be occurring, and, although at limited rates, leaching may be causing the migration of contaminants from the refuse toward the water table.

CONCLUSIONS

At each of these landfill sites in unsaturated materials, monitoring wells were unable to indicate the patterns and extent of leachate migration accurately. Soil samples collected for chemical analysis also yielded little information regarding leachate migration, and subsequent borings would have been necessary to define changes in soil-moisture chemistry—an expensive and time-consuming process.

The pressure-vacuum lysimeters used in this study have the advantage of providing soil-moisture samples repeatedly from unsaturated materials. This method may also be applicable for use in saturated materials where low permeabilities limit the use of standard monitoring wells or for monitoring zones of temporary saturation.

Regulations resulting in the increased use of the unsaturated zone for waste disposal should consider the study of unsaturated flow through and beneath waste disposal sites where standard ground-water monitoring techniques are not applicable. The recent development of effective and efficient procedures to monitor the unsaturated zone may be applicable to routine waste-disposal monitoring programs. Further research is also needed to evaluate the effectiveness of gravel drains and landfill liners as leachate collection systems in unsaturated materials.

PART II. LABORATORY STUDY*

INTRODUCTION

An accurate technique for the sampling of soil moisture has become increasingly important for the study of the movement and attenuation of contaminants in the subsurface. A common method of collecting soil moisture involves the use of porous, ceramic-cup samplers, more commonly called pressure-vacuum or suction lysimeters, initially tested by Wagner (1962). Substantial bias and variability have been found in soil-water samples of NO_3-N, PO_4-P, Na, K, Ca, and P by previous investigators (Hansen and Harris, 1975; Grover and Lamborn, 1970). Factors including intake rate, plugging of ceramic-cup pores, and sorption and screening of some ions produced as much as 60 percent range in sample concentrations (Hansen and Harris, 1975). Zimmerman, Price, and Montgomery (1978) found highly variable concentrations of NH_4 and PO_4 in samples from porous ceramic samplers in a laboratory comparison with porous Teflon® samplers. Wolfe (1967) found that new ceramic cups yield several milligrams per liter of Ca, Mg, Na, HCO_3, and SiO_2 after cleaning with dilute HCl acid. Wagner (1962) found no measurable sorption of NO_3-N. Levin and Jackson (1977), on the other hand, determined that porous-cup lysimeters were viable extraction devices for obtaining soil-water samples for determination of electrical conductivity for Ca, Mg, and PO_4-P, but that their suitability for NO_3-N was questionable.

Each of the previous studies utilized solutions of relatively low solute concentrations. Small sampling errors are quite apparent and may have significantly affected the interpretation of analytical results. Despite these problems, soil-water samplers have come into widespread use for monitoring highly contaminated soil solutions such as landfill leachate. The ability of these samplers to obtain representative samples of highly concentrated leachate has not been examined previously. Although sample variability and bias have been shown to adversely affect samples of solutions with low solute concentrations, this experiment attempted to determine the validity of samples of highly contaminated landfill leachate collected with ceramic-cup lysimeters.

MATERIALS AND METHODS

The pressure-vacuum lysimeters used in this study (Model 1920-Soil Moisture Equipment Corporation, Santa Barbara)† consisted of a porous ceramic cup, 2 inches (5 cm) outside diameter (O.D.) and 2.5 inches (6.4 cm) long attached to one end of a section of plastic (PVC) pipe (fig. 2). The opposite end was sealed with a two-hole rubber stopper into which two plastic (or copper) access tubes (0.25 in. [6.4 mm] O.D.) were inserted. One tube extended only a few centimeters into the lysimeter and was used to apply either air pressure or a vacuum to the sampler; the other tube, extending to the bottom of the lysimeter, allowed the water sample to flow to the surface. With a partial vacuum applied and the access tubes clamped shut, a buried porous cup sampler will collect soil moisture when tension, or vacuum, in the lysimeter is greater than the surrounding soil moisture tension.

The samplers were used to evaluate the validity of lysimeters for monitoring landfill leachate quality. One new, unused sampler that was not cleaned (NC) and one sampler that was cleaned with dilute hydrochloric acid and rinsed with distilled water (C) were placed in separate 5-gallon plastic carboys, each containing approximately four gallons of raw leachate. A constant flow of carbon dioxide gas was bubbled through the leachate to maintain reducing conditions and a constant pH.

The leachate was collected the day before the study began from a monitoring well (BL-2) finished in the refuse at the Blackwell Forest Preserve landfill in Du Page County (see Hughes, Landon, and Farvolden, 1971). The two plastic carboys were filled with leachate bailed from the well and CO_2 gas was passed over the leachate in the carboy during the sample collection period. The carboys were sealed and returned to the laboratory the same day. In order to measure the validity of the lysimeters for sampling trace metals, each leachate was immediately "spiked" with an additional 2.5 mg/L of Pb, Hg, and Cu. The following day the leachate was mixed thoroughly and a lysimeter was placed in each carboy. A vacuum of 55 centibars (413 mm Hg) was initially placed on each sampler using a portable hand pump. Lysimeter samples were collected from each lysimeter daily for 10 consecutive days using air pressure applied with the hand pump. These samples were acidified with dilute nitric acid and refrigerated in linear polyethylene bottles.

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*The laboratory study was conducted with the assistance of Rudy M. Schuller, Illinois State Geological Survey.

†Mention of trade names in this paper does not imply endorsement by the Illinois State Geological Survey or sponsoring agencies.

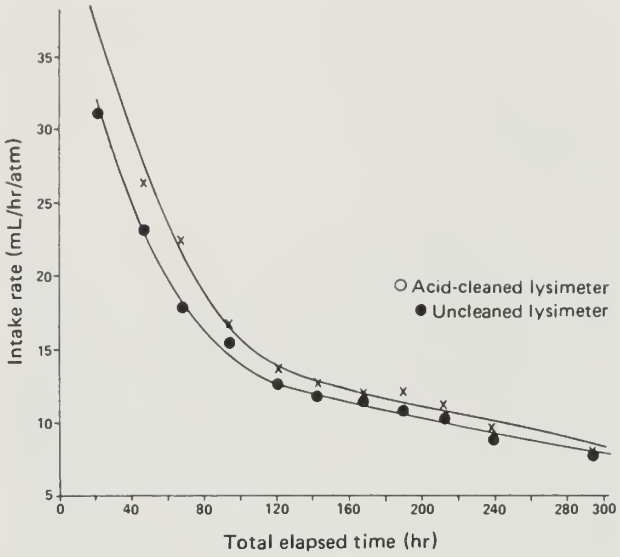

Figure 27. Intake rate (cup conductivity) of acid-cleaned and uncleaned lysimeters in landfill leachate versus elapsed time.

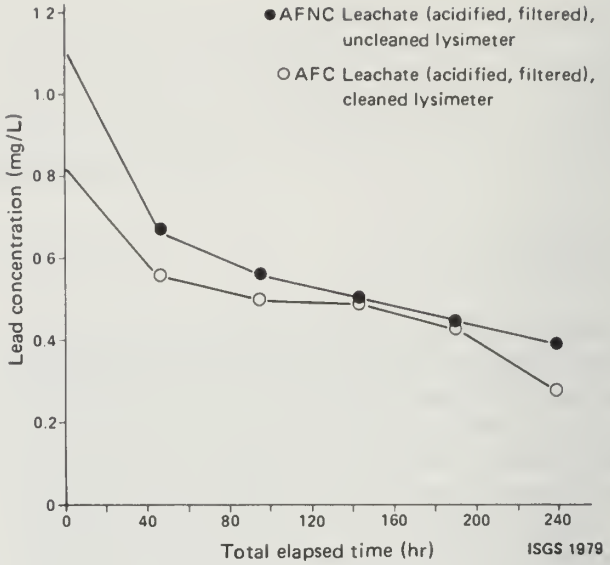
AFNC Leachate (acidified, filtered), uncleaned lysimeter
AFC Leachate (acidified, filtered), cleaned lysimeter
Lead concentration (mg/L)
Total elapsed time (hr)
ISGS 1979

Figure 28. Concentration of lead in samples of raw leachate versus elapsed time.

Duplicate samples of raw leachate were collected from each carboy the first day and every other day thereafter for 10 days. One sample (denoted AFNC or AFC) was immediately acidified and, after centrifuging, was filtered through a 0.7 μm pore size membrane filter. A similar sample (denoted FANC or FAC) was centrifuged, filtered, and then acidified prior to refrigeration. The large amount of suspended particulate matter in the raw leachate required that the samples be centrifuged prior to filtration. Samples of raw leachate were filtered through a 0.7 μm pore size membrane filter in an attempt to simulate the pore diameter of the porous ceramic cups of the lysimeters that have an effective pore diameter of approximately 1 μm. The samples were analyzed for Ca, Mg, Na, K, Fe, Zn, Pb, Hg, and Cu by standard atomic adsorption techniques (U.S. EPA, 1974) and Cl by specific ion electrode.

RESULTS

Intake rate

The intake rate and, hence, volume collected from each lysimeter decreased steadily with time. The decrease in intake rate, or cup conductivity, is illustrated in figure 27 as volume collected per unit time per atmosphere of applied vacuum. During the first 5 days, the intake rate of each sampler decreased rapidly; subsequently, the decrease, although steady, was at a much lower rate. The intake rate of the acid-cleaned lysimeter after 11 days was 22 percent of the initial rate. The uncleaned sampler had decreased to 25 percent of its initial intake rate after 11 days.

The effects of acid treatment of the ceramic cup may be reflected by the consistently larger sample volumes and intake rate of the acid-cleaned lysimeter. Sample volumes collected from the acid-cleaned sampler ranged from 12 to 21 percent greater than those from the uncleaned lysimeter. Although cleaning with acid may cause a slight increase in intake rate (cup conductivity), this experiment indicated that these effects decrease with time in raw leachate.

The decrease in yield of the samplers was probably the result of clogging of the small pores on the exterior of the ceramic cup by suspended particulate matter in the leachate. Microbial growth also may have contributed to clogging of pores. Upon completion of the experiment, the ceramic cups withdrawn from the leachate had a thin residue on their exterior which, when rinsed off, revealed a relatively clean ceramic surface underneath.

This decrease in yield, however, was not observed during field studies of identical lysimeters described in Part I. Sample volume remained relatively constant from samplers at each of the three landfill sites studied. Hansen and Harris (1975) stated that "ceramic cups plug up when used in the field." This was the case for the two lysimeters directly immersed in raw leachate; however, the suspended particulate matter primarily responsible for clogging of the ceramic cups is easily removed from leachate during migration through sediments beneath a landfill. Although microbial growth and plugging by colloids may still occur following migration through soils, these do not appear to have markedly affected the field performance of lysimeters.

Chemical analyses

The results of the chemical analyses are presented in table 12 and the mean and standard deviation of the results are included in table 13. Table 14 includes the results of statistical analyses of a comparison of the variances (F-statistic) and differences of means (Student's t-test) of lysimeter samples (NC, C) and raw leachate (FANC,

TABLE 12. Chemical composition of lysimeter samples and raw leachate.

Sample no.	Elapsed time (hr)	Volume (mL)	Concentration (mg/L) Ca	Mg	Na	K	Fe	Zn	Pb	Cl
1NC	21.5	360	353	177	581	35.0	1,584	11.3	<0.2	1,225
2NC	46.3	290	351	177	594	35.6	1,616	9.9	<0.2	1,238
3NC	68.0	220	343	171	600	37.5	1,584	9.6	<0.2	1,238
4NC	93.8	215	347	177	575	35.0	1,568	9.5	<0.2	1,225
5NC	120.0	180	335	169	519	35.0	1,600	9.0	<0.2	1,238
6NC	142.5	152	337	173	550	34.4	1,507	8.0	<0.2	1,225
7NC	167.0	152	343	173	575	35.6	1,568	8.2	<0.2	1,225
8NC	189.8	140	344	175	586	35.0	1,568	7.7	<0.2	1,238
9NC	213.5	132	339	174	588	36.9	1,568	10.0	<0.2	1,238
10NC	239.3	132	344	177	556	34.4	1,536	9.0	<0.2	1,238
1FANC	0	250	349	171	563	34.4	1,552	12.7	<0.2	1,225
2FANC	46.3	250	350	178	463	28.8	1,277	10.2	<0.2	1,211
3FANC	93.8	250	350	178	463	36.3	1,568	9.5	<0.2	1,225
4FANC	142.5	250	350	178	581	35.0	1,568	8.9	<0.2	1,211
5FANC	189.8	250	345	175	581	34.4	1,552	7.7	<0.2	1,238
6FANC	239.3	250	348	176	556	34.4	1,568	6.6	<0.2	1,211
1AFNC	0	250	361	182	638	37.5	1,577	13.6	1.11	1,211
2AFNC	46.3	250	350	175	594	37.5	1,533	12.1	0.67	1,238
3AFNC	93.8	250	355	178	569	35.6	1,488	10.6	0.56	1,238
4AFNC	142.5	250	359	175	600	36.9	1,518	10.0	0.50	1,238
5AFNC	189.8	250	350	173	594	37.5	1,518	9.3	0.44	1,225
6AFNC	239.3	250	350	175	575	35.0	1,473	8.3	0.39	1,225
1C	22.0	435	324	158	494	30.6	1,455	9.0	<0.2	1,238
2C	46.5	330	354	175	575	34.4	1,568	9.1	<0.2	1,225
3C	68.1	260	348	173	531	34.4	1,455	8.4	<0.2	1,211
4C	93.8	230	349	170	538	34.4	1,519	7.7	<0.2	1,238
5C	120.0	195	349	170	563	35.0	1,616	10.4	<0.2	1,238
6C	142.5	162	350	175	575	34.4	1,519	9.2	<0.2	1,238
7C	167.0	160	348	175	556	34.4	1,519	10.4	<0.2	1,238
8C	189.8	150	343	173	556	33.1	1,519	7.8	<0.2	1,238
9C	213.5	142	340	170	563	34.4	1,600	9.6	<0.2	1,238
10C	239.3	148	352	178	563	34.4	1,584	7.7	<0.2	1,238
1FAC	0	250	331	161	575	35.0	1,536	10.9	<0.2	1,238
2FAC	46.5	250	343	176	569	34.4	1,519	10.3	<0.2	1,225
3FAC	93.8	250								
3FAC	93.8	250	359	181	594	35.0	1,536	10.5	<0.2	1,238
4FAC	142.5	250	351	175	575	34.4	1,536	8.3	<0.2	1,251
5FAC	189.8	250	368	179	588	35.6	1,536	6.8	<0.2	1,238
6FAC	239.3	250	351	175	575	35.6	1,568	6.7	<0.2	1,238
1AFC	0	250	354	174	969	41.3	1,518	12.9	0.83	1,158
2AFC	46.5	250	350	177	588	34.4	1,429	11.5	0.56	1,211
3AFC	93.8	250	350	177	581	34.4	1,429	11.6	0.50	1,225
4AFC	142.5	250	354	177	594	37.5	1,429	9.6	0.50	1,225
5AFC	189.8	250	350	178	581	33.8	1,429	8.7	0.44	1,238
6AFC	239.3	250	350	178	650	36.3	1,473	7.6	0.28	1,238

AFNC, FAC, AFC). As noted previously, the leachate in each container was "spiked" with the addition of solutions of Pb, Hg, and Cu to produce additional concentrations of approximately 2.5 mg/L. This was done in an attempt to ensure measurable quantities of trace elements in the raw leachate. Samples of leachate withdrawn from each container concurrently with lysimeter samples were used to determine the ability of lysimeters to provide representative samples for chemical analysis. The filtering of leachate samples prior to acidification is a common procedure for the sampling and preservation of contaminated water samples (Wood, 1977). Acidification prior to filtration, on the other hand, should produce an increase in the concentrations of some elements as a result of the partial dissolution of suspended particulate matter and exchange of cations from suspended colloids.

TABLE 13. Mean and standard deviation of chemical analyses of lysimeter samples and raw leachate.

	No. of samples	Mean (mg/L)	Standard deviation
Ion	N	X	S
Ca-NC	10	343.6	5.7
FANC	6	348.7	2.0
AFNC	6	354.2	5.0
C	10	345.7	8.6
FAC	6	350.5	12.8
AFC	6	351.3	2.1
Mg-NC	10	174.3	2.83
FANC	6	176.0	2.76
AFNC	6	176.3	3.2
C	10	171.7	5.5
FAC	6	174.5	7.0
AFC	6	176.8	1.5
Na-NC	10	572.3	24.4
FANC	6	534.4	56.6
AFNC	6	594.8	24.2
C	10	551.3	24.6
FAC	6	579.2	9.4
AFC	6	660.5	153.3
K-NC	10	35.4	1.02
FANC	6	33.9	2.6
AFNC	6	36.7	1.1
C	10	34.0	1.3
FAC	6	35.0	0.5
AFC	6	36.3	2.8
Cl-NC	10	1,232.8	6.7
FANC	6	1,220.2	11.1
AFNC	6	1,229.2	10.9
C	10	1,234.0	9.1
FAC	6	1,238.0	8.2
AFC	6	1,215.8	30.1
Fe-NC	10	1,569.9	30.8
FANC	6	1,514.2	116.5
AFNC	6	1,517.8	36.4
C	10	1,535.4	55.9
FAC	6	1,538.5	16.0
AFC	6	1,451.2	37.2
Zn-NC	10	9.2	1.10
FANC	6	9.3	2.10
AFNC	6	10.7	1.90
C	10	8.9	1.03
FAC	6	8.9	1.90
AFC	6	10.3	2.01
Pb-NC	10	< 0.2	
FANC	6	< 0.2	
AFNC	6	0.6	0.26
C	10	< 0.2	
FAC	6	< 0.2	
AFC	6	0.5	0.18
Hg		ND	
Ca		ND	

Although each container of leachate initially contained at least 2.5 mg/L of Cu, Pb, and Hg, no Cu or Hg was detected in any of the samples collected during this study. Pb was present in steadily decreasing amounts only in AFC and AFNC leachate samples which were acidified prior to filtration (fig. 28). Apparently, these trace elements were adsorbed onto particulate matter in the leachate or precipitated and progressively settled out of the suspension. Filtration through a membrane filter or a ceramic cup effectively removed all particles containing adsorbed Pb.

Zn concentrations of 6.6 to 13.6 mg/L were detected in leachate and lysimeter samples. Samples of raw leachate that were acidified prior to filtration (AFNC, AFC) contained a consistently greater amount of Zn than those samples filtered prior to acidification (FANC, FAC) (fig. 29). Similar to the case of Pb, concentrations of Zn in samples of raw leachate decreased markedly with time. Linear regression analysis indicated a highly significant linear correlation ($r^2 > 0.99$) of Zn with elapsed time in samples of raw leachate from each container. Zn concentrations in lysimeter samples were not nearly as predictable. Samples from the uncleaned lysimeter (NC) contained levels of Zn very similar to that of the filtered-acidified leachate samples for approximately the first 190 hours. Subsequent analyses varied greatly, occasionally even containing more Zn than acidified-filtered leachate. Although Zn concentrations from the acid-cleaned lysimeter (C) varied greatly, they did not decrease with time as did Zn concentrations in leachate samples from the same container (fig. 29). Although Zn concentrations appeared to decrease with time and exhibited marked fluctuations, results of statistical tests indicated that there were no significant differences between either the means of the variances of the NC lysimeter samples and raw leachate from the same container and also between the C lysimeter samples and FAC leachate samples. A comparison of C lysimeter samples and AFC leachate samples showed significant differences ($\alpha > 95\%$) between the variances of the two samples and highly significant differences ($\alpha > 99\%$) between the means of the samples. Many of the parameters exhibited significant differences between means and variances of C lysimeter samples and AFC leachate samples (table 14). The reasons for this are not clear although occasional anomalous concentrations in AFC samples appear to have affected the comparison.

The steady decrease of Zn concentrations in leachate with time and the greater Zn content of AF than FA samples probably reflect the progressive settling out of the leachate of particulate matter containing adsorbed Zn. Chemical precipitation may also have reduced the amount of Zn in solution. The reasons for the general lack of correlation with time of Zn from the C lysimeter and the change after 190 hours in the NC lysimeter are unknown.

Total iron (Fe) concentrations were very high and fairly consistent in all samples (tables 12 and 13). The iron was presumed to be virtually all in the ferrous (Fe^{+2})

TABLE 14. Comparison of variances (F-statistic) and differences of means (t-statistic) between lysimeter samples (NC, C) and raw leachate (FANC, AFNC, FAC, AFC).

Ion	NC-FANC		NC-AFNC		C-FAC		C-AFC	
	F	t	F	t	F	t	F	t
Ca	8.46[a]	2.07	1.33	3.75[b]	2.19	0.90	17.45[b]	1.55
Mg	1.05	1.17	1.28	1.33	1.64	0.89	13.95[b]	2.21[a]
Na	5.31[a]	-1.89	1.01	1.80	6.68[a]	2.63[a]	38.84[b]	2.25[a]
K	6.48[a]	-1.72	1.16	2.26[a]	5.58[a]	1.91	4.97[a]	2.29[a]
Fe	14.28[b]	-1.46	1.40	-3.06[b]	12.24[b]	0.13	2.26	-3.26[b]
Zn	3.82	0.06	3.17	1.92	3.45	-0.02	5.43[a]	-8.87[b]
Cl	2.74	-2.86[a]	2.66	-0.83	1.21	0.88	11.02[b]	-1.82

[a]Significant at the 0.05 level.
[b]Significant at the 0.01 level.

state owing to the reducing conditions of the leachate. The variance of Fe in NC lysimeter samples (fig. 29) was generally very similar to that of AFNC leachate samples from the same barrel; however, there was highly significant difference ($\alpha > 99\%$) between NC and FANC samples (table 14). A single FANC sample collected after 46 hours contained anomalously low amounts of Fe (1277 mg/L), almost certainly the result of sampling error. Neglecting this value the standard deviation of Fe in lysimeter samples was only 2 percent of the mean Fe concentration in FANC leachate samples and the difference between NC and FANC variances was probably significant ($\alpha > 95\%$). There was no significant difference between means of Fe in NC and FANC samples. This was the case for all other parameters except chloride. However, the mean Fe concentrations in NC lysimeter samples and AFNC were significantly different ($\alpha > 99\%$). Interestingly, the Fe content of AFNC leachate samples was not greater than that of FANC samples indicating that the dissolution of particulate matter prior to filtration did not contribute measurable amounts of Fe to the samples. The results indicate that the levels and variation of Fe observed in NC lysimeter samples were in general very similar to those of the raw leachate being sampled.

Fe concentrations from C lysimeter samples (fig. 29) were quite variable, while FAC leachate samples also contained more Fe than AFC samples. However, the standard deviation of Fe in C lysimeter samples was still only 4 percent of the mean of the FAC leachate samples and their means were nearly identical (table 14). Lysimeter samples exhibited considerably more variability than FAC samples, possibly caused by the use of an air pump for sampling

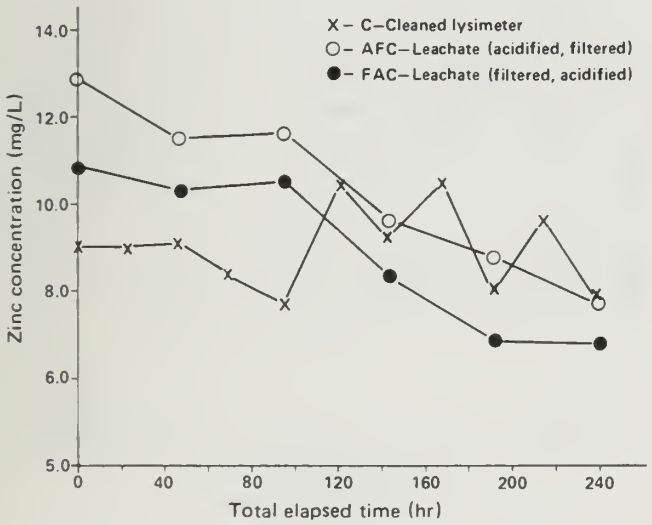

Figure 29a. Zinc concentration in samples obtained from an acid-cleaned lysimeter compared with samples of raw leachate during a 240-hour period.

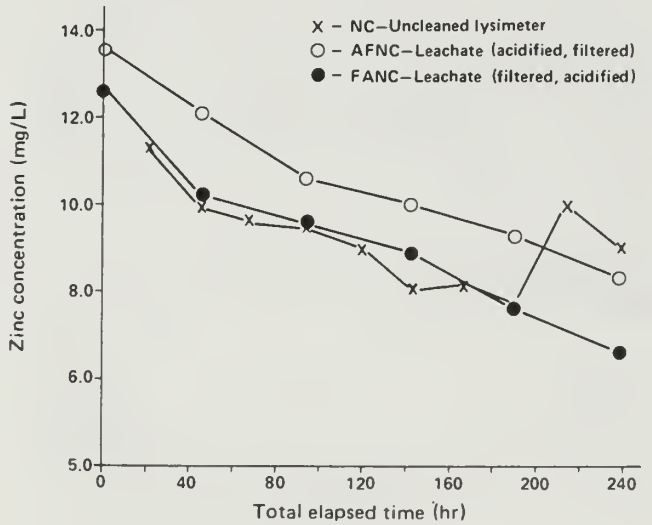

Figure 29b. Zinc concentration in samples obtained from an uncleaned lysimeter compared with samples of raw leachate during a 240-hour period.

Figure 29a-n. Concentrations of major ions in samples obtained from acid-cleaned (C) and uncleaned (NC) lysimeters compared with samples of raw leachate. Concentrations are compared for a 240-hour period of time (10 days).

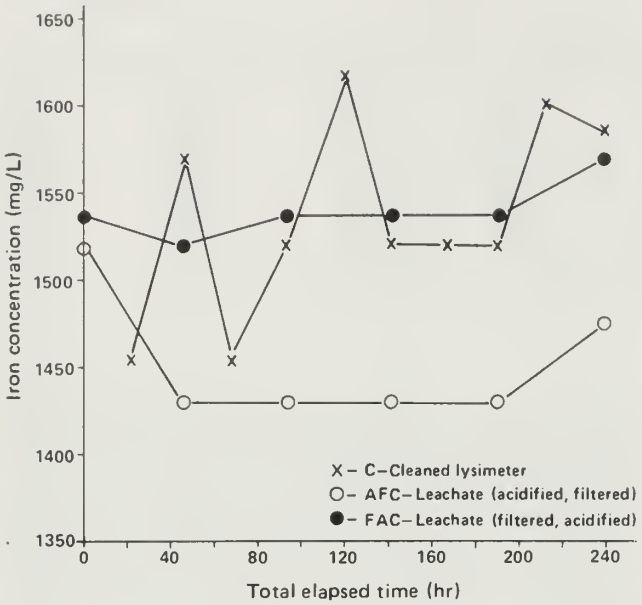

Figure 29c. Iron concentration in samples obtained from an acid-cleaned lysimeter compared with samples of raw leachate during a 240-hour period.

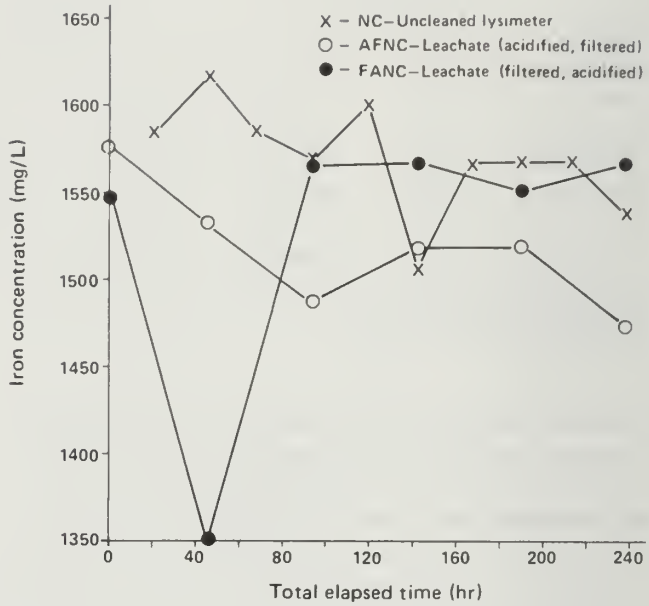

Figure 29d. Iron concentration in samples obtained from an uncleaned lysimeter compared with samples of raw leachate during a 240-hour period.

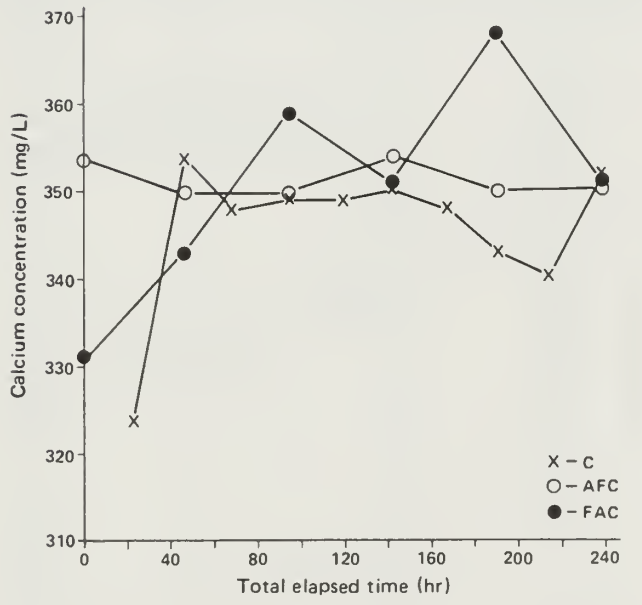

Figure 29e. Calcium concentration in samples obtained from an acid-cleaned lysimeter compared with samples of raw leachate during a 240-hour period.

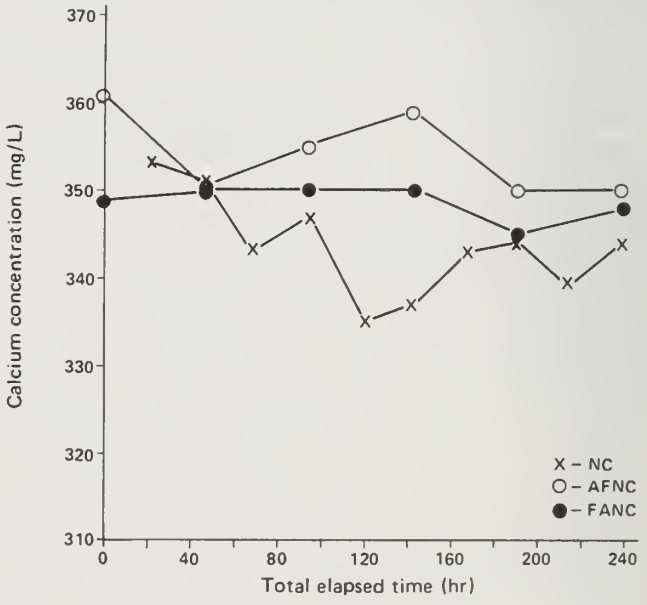

Figure 29f. Calcium concentration in samples obtained from an uncleaned lysimeter compared with samples of raw leachate during a 240-hour period.

Figure 29c-f. *(continued)*

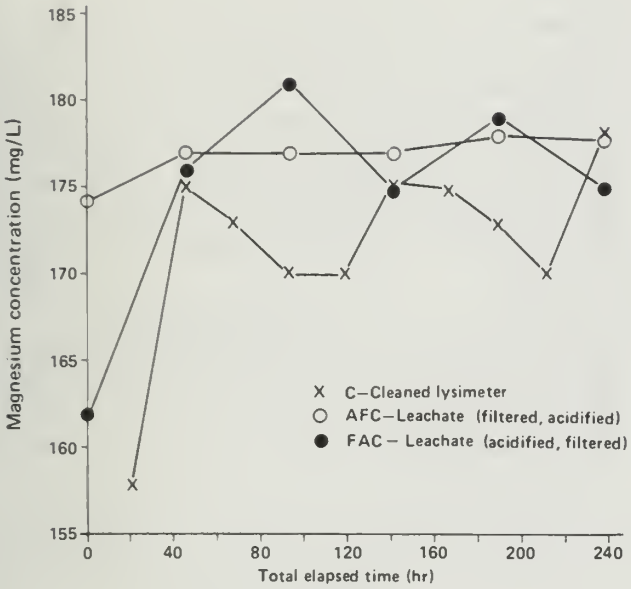

Figure 29g. Magnesium concentration in samples obtained from an acid-cleaned lysimeter compared with samples of raw leachate during a 240-hour period.

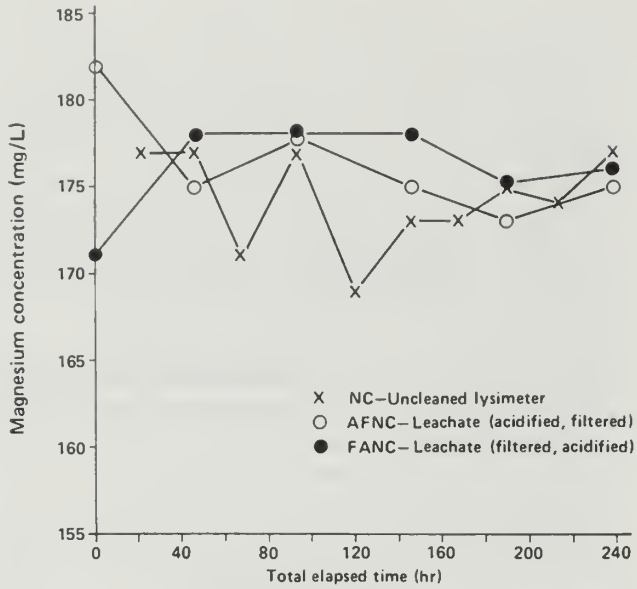

Figure 29h. Magnesium concentration in samples obtained from an uncleaned lysimeter compared with samples of raw leachate during a 240-hour period.

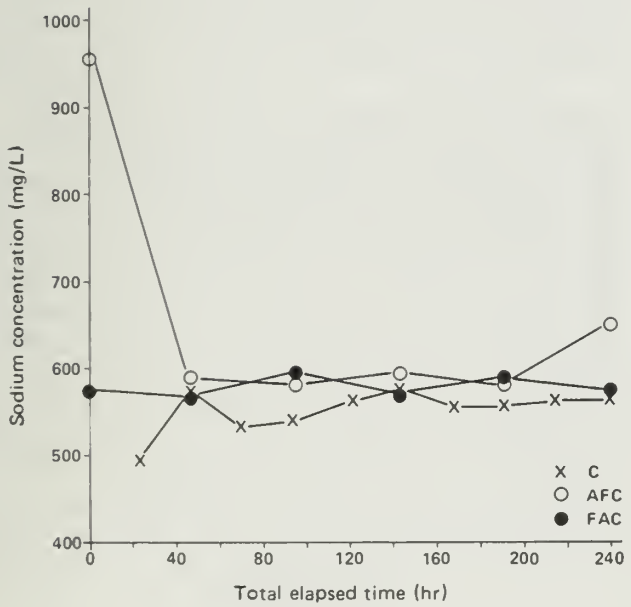

Figure 29i. Sodium concentration in samples obtained from an acid-cleaned lysimeter compared with samples of raw leachate during a 240-hour period.

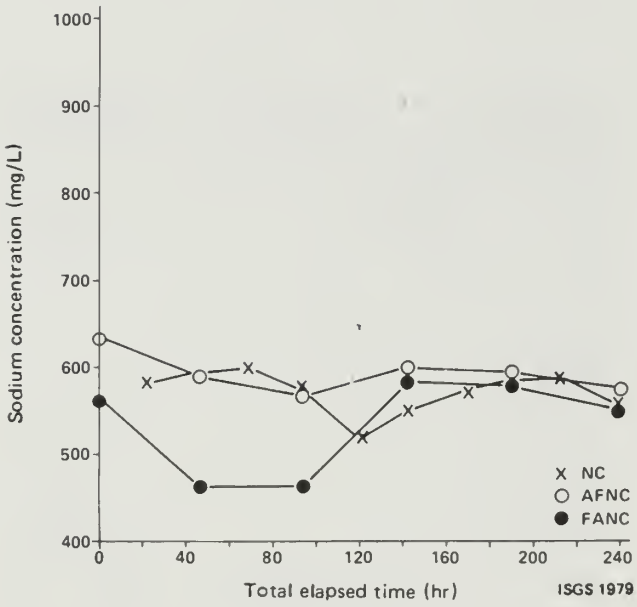

Figure 29j. Sodium concentration in samples obtained from an uncleaned lysimeter compared with samples of raw leachate during a 240-hour period.

Figure 29g-j. *(continued)*

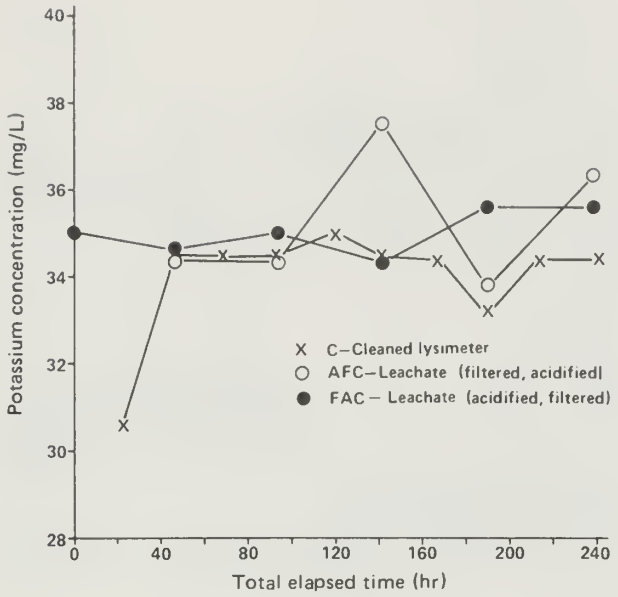

Figure 29k. Potassium concentration in samples obtained from an acid-cleaned lysimeter compared with samples of raw leachate during a 240-hour period.

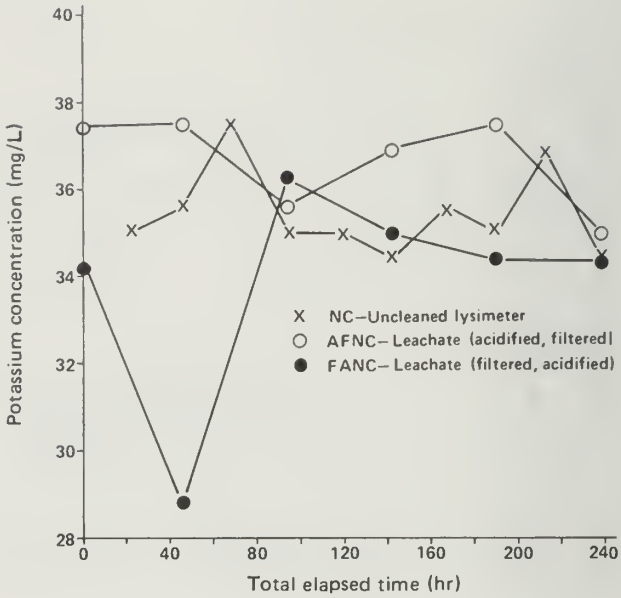

Figure 29l. Potassium concentration in samples obtained from an uncleaned lysimeter compared with samples of raw leachate during a 240-hour period.

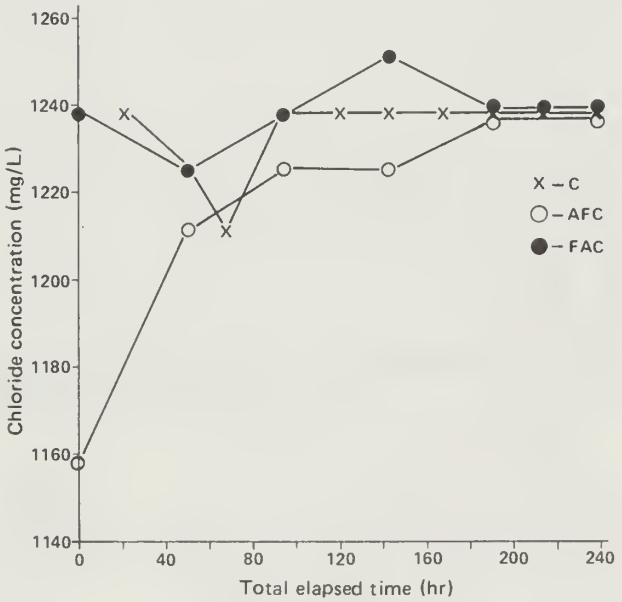

Figure 29m. Chloride concentration in samples obtained from an acid-cleaned lysimeter compared with samples of raw leachate during a 240-hour period.

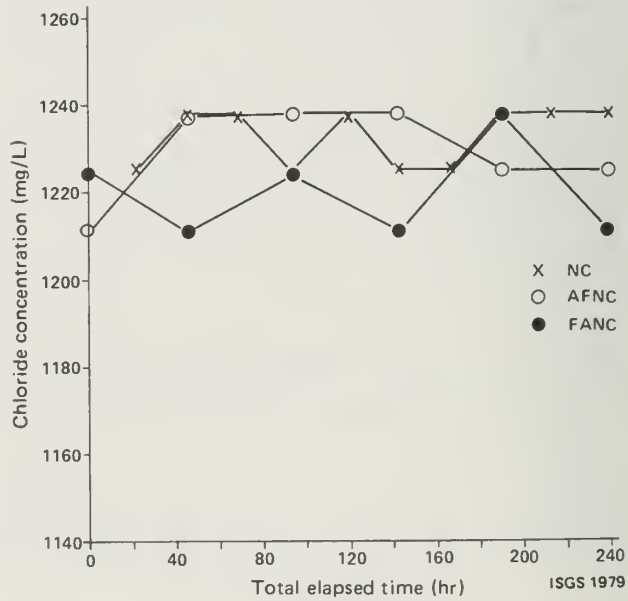

Figure 29n. Chloride concentration in samples obtained from an uncleaned lysimeter compared with samples of raw leachate during a 240-hour period.

Figure 29k-n. *(continued)*

the lysimeter. The Fe contents of FAC and AFC raw leachate samples, although different, were remarkedly consistent. The reasons for the general discrepancy between iron concentrations in AFC and FAC samples are unknown, but may have been due to desorption of iron from clay particles during filtration. Clay particles may also have passed through the 0.7 μm filter membrane and more iron may have been dissolved because of longer contact time.

The remaining parameters used in the experiment included Ca, Mg, Na, K, and Cl. All of these are relatively mobile and, under these experimental conditions, generally nonreactive. The concentrations of each parameter were generally very high, representative of leachate only a few years old (table 13). The variation of each of these parameters with time is shown in figure 29. In general, the data indicate a great deal of similarity between lysimeter and raw leachate samples. Mean concentrations and standard deviations for lysimeter samples closely approximate those of raw leachate samples. Although significant differences ($\alpha >$ 95%) were found between the variances of NC and FANC concentrations of Ca, Na, K, and Fe, there were no significant differences between mean concentrations in NC lysimeter samples and FANC leachate samples (table 14). Significant differences between the means of NC and AFNC samples were found for Fe, Ca, and K, but differences between mean concentrations from the acid-cleaned lysimeter (C) and FAC samples were in general not significant. The standard deviations of leachate analyses are in general nearly identical to those of samples from lysimeters for Ca, Mg, Na, K, and Cl.

Linear regression data showed no significant correlation with time by any of these five parameters: Ca, Mg, Na, K, and Cl, indicating that the leachate in general remained chemically stable during the experiment. The deviations of sample concentrations of Ca, Mg, Na, K, and Cl that did occur seemed to be explainable in terms of variable leachate composition, sampling procedures, and accuracy of analysis. Although some degree of sorption and screening of ions undoubtedly occurred on the ceramic cup, the effects appeared to be negligible compared to the concentrations of each ion present in the leachate. No consistent, measurable differences in concentrations were found between lysimeter and raw leachate samples which could be attributed to sorption or screening by the lysimeter.

SUMMARY

Some studies have questioned the validity of chemical analysis of soil-water samples collected by pressure-vacuum lysimeters having porous ceramic cups (Hansen and Harris, 1975; Grover and Lamborn, 1970). However, these studies measured the concentrations in samples of relatively dilute (less than 20 mg/L) solutions, the results of which are very susceptible to sample collection bias. Sample variability or bias of several milligrams per liter may be quite significant when tracing the movement of soil water of low solute concentrations; however, the effects of this variability or bias upon highly contaminated leachate for most common ions were concluded to be negiligible. Although attempts to sample trace elements such as Pb, Cu, and Zn were generally unsuccessful in this study, this does not appear to have been caused by the ceramic cups. The loss of Pb, Cu, Hg, and Zn in the leachate appeared to be caused by adsorption by clay particles that were removed from the leachate suspension by settling prior to passage through the ceramic cup. Pb, Cu, Hg, and Zn in leachate beneath actual disposal sites would probably be removed by sediments during migration prior to sampling. Samples from lysimeters were generally very representative of the surrounding leachate composition of major ions (Ca, Mg, Na, K, Cl, and Fe). However, further experiments are required to determine the ability of ceramic-cup samples to obtain representative concentrations of certain trace elements and organic compounds. The use of relatively pure solutions of individual elements may be necessary to eliminate the effects of highly contaminated leachate on these constituents in future experiments.

ACKNOWLEDGMENTS

This research project was performed by the Illinois State Geological Survey under Contract No. 40.029 with the Illinois Institute of Natural Resources, Project Officer Larry Hardin. The project was conceived and initiated by Thomas Clark, Illinois Environmental Protection Agency (IEPA). Tom and Dr. Rauf Piskin (IEPA) aided in the planning of the study and selection of landfill sites.

The authors wish to thank the owners and operators of the three landfills for permitting the studies to be conducted on their properties, for tolerating the inconvenience of our operation, and for providing us with background information. John Veugeler, Robert Veugeler, and James Veugeler, owners of the Crystal Lake landfill, and Lawrence Lievens, Director of Public Works, Geneseo, Illinois, gave their time and cooperation throughout the study.

Many persons at the Survey assisted in the study. Gary Patterson and Bonnie Witek assisted with the field and laboratory aspects of this project. Edward G. Scoggin operated the drilling rig at each site. Chemical analyses of water and soil samples were conducted under the direction of Dr. Neil F. Shimp, Dr. Rodney R. Ruch, and Dr. Robert Griffin. Dr. Herbert Glass conducted the clay mineral analyses, and the textural analyses were supervised by Dr. W. Arthur White. Dr. Robert Griffin reviewed the manuscript and provided many helpful suggestions during the study. Additional chemical analyses were provided by the IEPA and the Illinois State Water Survey.

The authors gratefully acknowledge the cooperation and assistance of all these persons and agencies and extend to them our sincere gratitude.

APPENDIX 1.

Data for installation of monitoring wells

Well no.	Ground surface elevation[a] (ft)	(m)	Depth of screened interval (ft)	Material	Date installed	Comments
GENESEO LANDFILL						
P-4	674.34	(205.58)	60.0-64.0	Sand	5/19/76	ISGS[b]
P-5	633.20	(192.99)	26.1-28.1	Sand	5/19/76	ISGS[b]
P-6	652.05	(198.74)	37.0-41.0	Sand	5/20/76	ISGS[b]
P-9	645.0	(196.59)	28.0-32.0	Sand and gravel	8/3/76	ISGS[b]
P-12	634.53	(193.40)	37.0-40.0	Sand	8/5/76	ISGS[b]
P-13	640 est.	(195.1)	est. 38-43	Sand?	1967-1975?	Old monitoring well near canal
P-14	653 est.	(199.1)	est. 39-44	Sand?	1967-1975?	Old monitoring well near P-4
P-15	675 est.	(205.8)	77.0-83.0	Sand and gravel	6/1/77	TEI[c]
P-16	657 est.	(200.3)	est. 55	Sand	?	Hand pump—aban.
SAVANNA LANDFILL						
P-1	122.86	(37.45)	40.6-45.6	Sand	2/6/74	TEI[c]
P-2	102.42	(31.22)	29.5-34.5	Sand	2/6/74	TEI[c]
P-4	109.71	(33.44)	48.8-50.3	Silty sand	4/7/76	ISGS[b]
P-5	117.22	(35.73)	29.3-33.3	Sand and gravel	5/25/76	ISGS[b]
P-6	117.22	(35.73)	44.3-45.3	Sand and gravel	5/26/76	5 ft (1.5 m) south of P-5—ISGS[b]
P-7	110.45	(33.66)	20.0-24.0	Sand	5/26/76	ISGS[b]
CRYSTAL LAKE LANDFILL						
P-6	884.51	(269.59)	36.6-40.6	Silty sand	5/13/76	10 ft (3.1 m) west of P-8—ISGS[b]
P-7	875.40	(266.81)	41.6-46.6	Sand	6/8/72	TEI[c]
P-8	885.03	(269.74)	55.0-60.0	Silty sand	6/8/72	TEI[c]
P-9	896.28	(273.17)	68.6-73.6	Sand	6/9/72	TEI[c]
P-10	872.71	(265.99)	40.0-45.0	Sand	6/9/72	TEI[c]
P-11	889.69	(271.16)	46.0-49.0	Silty sand	4/14/76	5 ft (1.5 m) east of fill—ISGS[b]
P-12	900 est.	(274.3)	20.0-24.0	Base of refuse	5/4/76	Samples water ponded on liner. ISGS[b]

[a] Elevation above m.s.l. except Savanna where above arbitrary datum.
[b] Installed by Illinois State Geological Survey.
[c] Installed by Testing Engineers, Inc.

APPENDIX 2.

Data for installation of pressure-vacuum lysimeters.

Boring	Lysimeter no.	Ground surface elevation (ft)	(m)	Depth of lysimeter tip (ft)	(m)	Material sampled	Depth below refuse* (ft)	Date installed	Comments
GENESEO LANDFILL									
G-S-1	SL-3	657.77	200.48	17.5	5.33	Sand	1.0	2/25/76	Refuse to 16.5 ft (5.0 m).
	SL-2			21.8	6.64	Sand	5.3		
	SL-1			30.0	9.14	Top of till	13.5		
G-S-3	SL-3	670.50	204.36	18.0	5.49	Sand	5.5	2/26/76	Refuse to 12.5 ft (3.8 m).
	SL-2			24.5	7.47	Sand	12.0		
	SL-1			32.0	9.75	Sand	19.5		1 ft (.3 m) above till.
G-S-7	SL-2	673.27	205.20	19.0	5.79	Sand	17.0*	7/22/76	No refuse encountered.
	SL-1			29.0	8.84	Sand	27.0*		
G-S-8	SL-2	674.13	205.47	8.5	2.59	Sand	3.5	7/22/76	Refuse to 5 ft (1.5 m).
	SL-1			23.0	7.01	Sand	18.0		
G-S-10	SL-1	674.10	205.46	30.0	9.14	Sand	25.0	8/4/76	Refuse to 5 ft (1.5 m).
SAVANNA LANDFILL									
S-S-1	SL-2	125.0	38.10	19.3	5.88	Sand	2.3	3/31/76	Refuse to 17 ft (5.2 m).
	SL-1			25.5	7.77	Silty sand	8.5		SL-2 never worked.
S-S-2	SL-1	125.0	38.10	24.0	7.31	Refuse	0	7/27/76	Samples leachate from base refuse.
S-S-3	SL-2	110.0	33.50	9.0	2.74	Sand	15.0*	7/26/76	No refuse encountered.
	SL-1			19.0	5.79	Sand	20.0*		
S-S-4	SL-1	129.0	39.30	34.0	10.36	Sand	9.0	4/8/76	Installed in hand auger boring prior to refuse disposal. Destroyed Aug. 1977.
S-S-5	SL-2	110.0	33.50	6.5	1.98	Sand	6.0*	7/27/76	5 ft (1.5 m) west of fill.
	SL-1			17.0	5.18	Sand	20.0*		SL-1 never worked.
S-S-6	SL-2	115.0	35.10	12.0	3.66	Sand	10.0*	7/27/76	5 ft (1.5 m) east of fill.
	SL-1			22.0	6.71	Sand	16.0*		
S-S-7	SL-1	115.0	35.10	24.5	7.47	Sand	23.0*	7/28/76	25 ft (7.6 m) north of fill.
CRYSTAL LAKE LANDFILL									
CL-S-3	SL-3	889.0	271.0	9.0	2.74	Sand, gravel	7.0*	5/6/76	10 ft (3.1 m) east of fill.
	SL-2			20.5	6.25	Silty sand	13.0*		
	SL-1			36.5	11.13	Silty sand	25.0*		
CL-S-4	SL-1	889.0	271.0	11.0	3.35	Sand	15.0*	5/6/76	12 ft (3.7 m) east of fill.
CL-S-5	SL-1	898.0	273.7	34.0	10.36	Silty sand	6.6	5/11/76	Refuse to 25 ft (7.6 m). Lysimeter 6.6 ft (2.2 m) below liner.
CL-S-7	SL-1	898.0	273.7	30.0	9.14	Silty sand	5.0	5/12/76	Refuse to 25 ft (7.6 m). Lysimeter 5.0 ft (1.5 m) below liner.

*Or distance from refuse.

[a]Elevation above m.s.l. except Savanna where above arbitrary datum.

Chemical analyses of soil samples.

Boring	Depth (ft)	Material	Ca (%)	Mg (%)	Fe (%)	K (%)	Na (%)	Hg (ppm)	Pb (ppm)	Zn (ppm)	Cl (%)	SO_4 (ppm)	Total C (%)	CEC (meq/100 g)	Comments
GENESEO LANDFILL															
G-S-1	18.0	Sand	0.24	0.11	0.59	0.97	0.52	0.04	<15	9.1	0.02	<.01	0.12	1.2	Overlain by 16 ft (4.9 m) of refuse
	21.0	Sand	0.18	0.07	0.45	0.96	0.51	0.02	<15	7.2	0.02	<.01	0.10	0.9	
	22.0	Silt	0.19	0.09	0.63	0.97	0.56		<30	9.2	0.01	<.01	0.19	1.3	
	23.0	Silty sand	0.23	0.14	0.81	0.96	0.55	0.04	<15	15.0	0.06	<.01	0.24		
	23.5	Silt	0.49	0.42	2.15	1.60	1.06	0.06	<15	41.4	0.03	<.01	0.40	8.9	
	27.0	Silty sand	0.49	0.41	2.02	1.61	1.11	0.05	<15	36.0	0.04	<.01	0.28	8.4	
	28.0	Silty sand	0.56	0.32	1.56	1.16	0.78	0.02	<15	18.0	0.18	<.01	0.35	1.8	
	29.0	Till	0.90	0.62	3.02	1.20	0.49	0.03	<15	42.8	0.21	<.01	0.46	2.2	
	30.0	Till	3.11	2.49	3.13	1.94	0.40	0.05	<15	62.0	0.09	<.01	0.37		
G-P-4	8.0	Silt	0.41	0.20	1.01	1.13	0.74		<25	22.3	0.03	<.01	0.37	2.5	Overlain by 5 ft (1.5 m) of refuse.
	28.0	Sand	3.02	1.49	1.20	1.21	0.96		<25	17.1	0.02	<.01	1.50	2.6	
	36.0	Sandy silt	5.11	3.16	2.48	1.88	0.59		<25	50.1	0.02	<.01	2.63	7.2	Oxidized sand.
	38.0	Till	6.17	3.84	2.73	2.22	0.36		<25	56.8	0.02	<.01	3.80	6.1	
G-P-5	7.0	Silt	0.33	0.17	1.11	1.11	0.70		<25	15.6	0.01	<.01	0.22	3.0	Uncontaminated,
	13.0	Silt	2.79	1.97	2.33	1.20	0.84		<25	51.3	0.01	<.01	1.82	4.6	500 ft (152.4 m) east of landfill.
	16.0	Clayey silt	5.13	3.51	2.85	2.39	0.48		<25	55.5	0.01	<.01	3.10	8.4	
	18.0	Sand	3.23	1.76	1.37	0.95	0.50		<25	28.6	0.02	<.01	2.08	0.6	
	22.0	Sand	2.57	1.00	0.59	0.96	0.56		<25	16.1	0.02	<.01	1.76	1.1	
G-P-6	16.0	Sand	2.61	1.21	0.97	1.04	0.52	.02	<22	15.0	0.02	<.01	1.24	1.7	Overlain by 12 ft (3.7 m) of refuse.
	28.0	Till	5.96	3.25	3.17	2.36	0.47	.10	<22	20.0	0.02	<.01	3.20	10.1	
SAVANNA LANDFILL															
S-S-1	21.0	Sand	2.09	0.77	1.00	1.24	0.96	.03	<22	52.0	0.02	<.01	0.96	2.3	Overlain by 16 ft (4.9 m) of refuse.
	24.0	Silty sand	4.37	2.14	2.04	1.56	0.59	.04	<22	48.0	0.03	<.01	2.03	8.1	
	33.0	Sand	2.22	0.65	1.22	1.02	0.36	.02	<22	14.0	0.02	<.01	0.73	1.2	
	38.0	Silty sand	1.17	0.77	1.94	1.14	0.70	.07	<22	56.0	0.02	<.01	0.68	23.0	
S-P-4	8.0	Sand	2.23	0.70	1.31	1.03	0.84	.04	<22	17.0	0.01	<.01	0.95	1.1	15 ft (4.6 m) west of landfill.
	15.0	Sand	1.70	0.51	1.06	1.14	0.48	.03	<22	16.0	0.02	<.01	0.71	1.2	
	36.0	Clayey silt	4.59	2.39	2.65	1.87	0.50	.06	<22	44.0	0.02	<.01	2.20	10.7	
S-P-5	6.0	Sand	0.36	0.19	0.78	1.19	0.84	.02	<15	11.0	0.62	<.01	0.13	1.8	25 ft (7.6 m) east of landfill.
	7.0	Sandy silt	3.63	2.26	1.95	1.56	1.08	.05	<15	42.0	0.35	<.01	2.05	8.5	
	13.0	Sand	1.13	0.40	0.65	1.02	0.70	.02	<15	10.0	0.04	<.01	0.66	1.1	
CRYSTAL LAKE LANDFILL															
CL-S-5	25.5	Till (liner)	8.76	4.23	1.83	0.98	0.53		<30	30.2	0.06	<.01	4.88	3.1	Overlain by 25 ft (7.6 m) of refuse.
	26.5	Till (liner)	9.72	4.99	1.46	1.17	0.56		<30	30.5	0.06	<.01	5.17	2.5	
	28.0	Silty sand	10.37	5.16	1.08	1.33	0.55		<30	26.0	0.04	<.01	5.93	1.1	
	30.0	Silty sand	10.01	5.18	1.09	1.34	0.56		<25	25.2	0.04	<.01	5.57	0.9	
CL-S-7	25.5	Till (liner)	6.95	3.95	2.35	1.19	0.59		<30	39.4	0.04	<.01	4.24	4.4	Overlain by 25 ft (7.6 m) of refuse.
	26.5	Till (liner)	6.33	3.51	2.31	1.14	0.57		<30	36.4	0.03	<.01	4.07	4.5	
	27.5	Sand	9.65	5.13	1.12	1.28	0.56		<30	25.1	0.04	<.01	5.59	1.1	
	28.5	Fine sand	6.60	3.14	2.66	0.75	0.37		<30	25.2	0.09	<.01	3.44	0.8	Oxidized sand
	30.5	Silty sand	9.71	4.60	1.18	1.36	0.56		<30	26.2	0.05	<.01	5.03	0.8	
CL-P-6	20.5	Silt	11.86	6.10	1.18	1.27	0.52		<25	25.9	0.04	<.01	6.75	1.4	Uncontaminated 200 ft (61 m) north of landfill.
CL-P-11	28.0	Sandy silt	10.97	5.76	1.14	1.34	0.53		<30	9.2	0.03	<.01	6.19	1.3	25 ft (7.6 m) east of landfill.

Note—All SO_4 concentrations less than 0.01 ppm.
*Analyses performed by the Illinois State Geological Survey, Urbana, Illinois.

Well no.	Date sampled	pH[b]	pH[c]	Alkalinity as $CaCO_3$ (mg/L)[b]	Alkalinity as $CaCO_3$ (mg/L)[c]	Specific conductivity (μmhos)[b]	Temp. (°C)[b]	Eh (mv)[b]	Total dissolved solids (mg/L)	COD (mg/L)	Chloride (mg/L)	Hardness as $CaCO_3$ (mg/L)	Nitrate-N (mg/L)
GENESEO LANDFILL													
G-P-4	8-31-76												
	3-18-77	7.10	8.00			470.	10.0		425	13.	19		0.7
	8-25-77	7.50		228.	306.	640.		+80	404.		14	375	0.3
G-P-5	7-23-76		7.24		262	650			331	882	13		2.0
	10-25-76		7.10		272	660			433	5	14		0.8
	10-25-76		8.20		260	588			762	91	15	360	
	3-18-77	7.20	7.76			480.			663	26	18		< .1
	8-25-77	7.65		212	248	710.		+78	494		30	401	0.8
G-P-6	8-31-76		7.57		514				669	321	65		3.0
	3-18-77	7.30	7.69			800	10.0		1,190	457	95		< .1
	8-25-77	7.78		295	352	740		+65	480		56	376	1.5
G-P-9	8-31-76												
G-P-12	8-31-76		7.29		300	670			511	1,071	40		0.1
	10-25-76		6.58		262	700			435	603	25		< .01
	10-25-76		8.20		248				540	780	37	360	
	3-18-77	7.17	7.56			505			477	584	40		0.3
	8-25-77	7.73		285	264	760		+80	512		58	368	0.3
G-P-13	3-18-77	7.18	7.95			355	10.0		140	4.7	4.5		4.1
G-P-14	3-18-77	7.35	7.86						470.	27	10		3.4
G-P-15	8-25-77	7.21			278	760	14.5	+62	502	300	40	397	0.5
SAVANNA LANDFILL													
S-P-1	3-17-77	7.46	8.17			405	9.0		380	2	21		2.7
S-P-2	6-30-77								384		11		
S-P-5	3-17-77	6.68	7.54			1,300			1,374	35	339		0.4
	1-5-77												
	8-24-77	7.06		140		1,555		+169	1,100	27	453		
S-P-6	3-17-77	7.35	8.04			400			320	620	8		0.3
	8-24-77	7.81		152		775		-15	280	438	18		
S-P-7	1-6-77	6.75	7.38	414		650	13.0		542	6	19		1.5
	3-17-77	6.72	7.68			605			613	15	16		0.7
	8-24-77	7.02		223		1,000		-95	545	17	18		
Plum River upstream	3-17-77	7.68	8.46			485			400	19	17		6.9
Plum River downstream	3-17-77	7.55	7.62			460			600	20	18		9.6
CRYSTAL LAKE													
CL-P-7	7-31-75		8.20		268	612			498	27	28	340	0.2
	8-23-77	8.00				660		+120	391	12	39		
CL-P-8	3-15-77	7.42	7.48			515			400	4.4	6		3.9
	8-23-77	7.63				385		+105	270	6	3		
CL-P-9	3-15-77	7.36	7.62			510			359	5	5		3.7
	8-23-77	7.82				595		+110	287	5	3		
CL-P-10	3-15-77	7.75	7.64			510			429	4	15		8.8
	8-23-77	8.00				655		+112	343	9	15		
CL-P-11	8-30-76		7.90		335				376	48	6	380	
	9-2-76		7.76		345	300			373	15	4		0.7
	3-15-77	7.88	7.51			290	13.5		254	10	9		1.8
	8-23-77	7.60		245		655	16.4	-35	302	17	17		
CL-P-12	1-4-77	5.65	5.64		11,800		9.0		22,750	30,500	1,602		
	3-15-77	5.45	5.24				18.0	+2	22,900	32,000	1,020		7.9
	8-23-77	5.50		5,589		12,000	16.4	-35					

[a] Analyses by the Illinois State Geological Survey unless noted otherwise.
[b] Field analyses upon sample collection.
[c] Laboratory recheck.

Chemical analyses of ground-water samples from monitoring wells and surface-water samples.

Ammonia–N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Iron (total) (mg/L)	Lead (mg/L)	Magnesium (mg/L)	Manganese (mg/L)	Mercury (ppb)	Potassium (mg/L)	Sodium (mg/L)	Zinc (mg/L)	Comments
		364	1.0	0.10	29		< .2	0.5	5.	0.5	
	58	61	0.3	< .01	19		< .01	< .01	4	0.08	
		91.5	1.0	< .01	35.6			1.2	5.2		Lab analyses
		348	0.95	< .01	28		< .2	1.0	9.0	0.16	by (ISWS)
		358	0.50	< .01	30		< .2	2.0	9.0	0.06	
0.36	94		0.60	< .01		0.15	< .2			0.2	(IEPA) dup-
	87	68	0.40	< .01	18		< .2	0.5	7.5	0.02	licate sample
	131	94.8	1.5	< .01	40			1.8	11.0		(ISWS)
		196	1.5	< .10	85		< .2	1.0	33.5	<.01	
	< .01	90	2.5	< .01	20		< .2	0.5	28.0	0.06	
	12	54	0.8		59		< .2	1.7	30.7		(ISWS)
		364	0.7	< .01	32		< .2	0.5	4.5	0.14	
		330	0.4	< .10	29		< .2	0.5	14	0.23	
		346	0.2	< .10	30		< .2	2.0	15	0.06	
0.34	82		0.4	0.02		0.26	< .2			0.2	(IEPA)
	79	66	0.2	< .01	19		< .2	1.5	14	0.06	
	90	87	0.1		37			2.5	32		(ISWS)
	38	42	.35	< .01	17			< .01	6.0	<.02	
	102	93	0.7		39.9			3.2	18.6		(ISWS)
	63	51	0.2	< .01	16			3.0	5.5	0.09	
			2.0								(IEPA)
	30	193	1.0	< .01	20		< .2	< .01	140	0.08	
	39	113	0.9	< .01	20			1.5	130	0.03	
	25	39	.35	< .01	19		< .2	3.5	5.0	0.08	
	102	75	7.00	< .01	19			0.5	15	0.07	
	103	76	0.80	< .01	19		< .2	0.5	15	0.13	
	46	47	0.3	< .01	19			3.0	8	0.19	At Wacker Rd.
	47	47	0.6	< .01	19			3.5	8	<.01	At railroad bridge.
0.16	50	61	0.4	0.02	38	0.65	< .2	2.2	6	0.2	(IEPA)
	40	47	0.4	< .01	19		< .2	0.50	2	0.58	
	36	48	0.45	< .01	18		< .2	< .01	2	0.20	
	67	54	0.2	< .01	19		< .2	0.5	5	0.08	
0.17	11	60	1.1	0.23	42	0.13	< .2	2.1	4		(IEPA)
		378	0.05	< .01	36		< .2	0.5	7	<.01	
	3	20	0.3	< .01	17		< .2	< .01	3	1.5	
		4,000		0.2	410			650	1,000	34.0	Samples refuse
	992	6,200	350	0.4	1660			640	1,030	46.5	(1973).

Boring	Lysimeter	Depth	Date sampled	pH[b]	pH[c]	Alkalinity as $CaCO_3$ (mg/L)[b]	Alkalinity as $CaCO_3$ (mg/L)[c]	Specific conductivity (μmhos)[b]	Temp. (°C)[b]	Eh (mv)[b]	Total dissolved solids (mg/L)	COD (mg/L)	Chloride (mg/L)
GENESEO LANDFILL													
G-S-1	SL-3	18 ft (5.5 m)	7-23-76										
			8-5-76										
			8-31-76										
			6-2-77		8.53			1,800			6,700	67	240
			8-25-77	6.95		948		2,850	17.2	-19	1,858	55	277
	SL-2	22 ft (6.7 m)	7-23-76		7.67		1,076				1,934	239	268
			8-5-76		7.53		863				1,935	535	290
			8-31-76		7.42		857				1,950	491	270
			3-18-77	7.05							1,496	166	285
			6-2-77		7.52			1,590			1,900	142	680
			8-25-77	6.83		830			16.5	-96	1,518	81	342
	SL-1	30 ft (9.1 m)	7-23-76		7.32		1,384				3,963	335	1,320
			8-5-76										
			8-31-76										
			6-2-77		7.20		5,500		17.0		8,500	574	3,410
			8-25-77	6.92		840	9,410		17.0	-76	7,725	247	3,583
G-S-3	SL-3	18 ft (5.5 m)	7-23-76										
			8-5-76										
			8-31-76										
			10-25-76		6.80						5,240	3,760	150
			2-8-77	6.55	6.87			1,900			4,603	3,300	145
			3-18-77	6.48	6.84			2,250	8.0		4,861	3,852	143
			6-2-77		6.72		3,100	2,300	13.5		5,100	3,738	210
			8-25-77	6.75		1,920		4,150	17.5	-95	4,899	3,131	166
	SL-2	25 ft (7.6 m)	7-23-76										
			8-5-76		7.19		2,680				5,676	3,110	346
			8-31-76								6,403	3,764	381
			2-8-77	6.70	6.60		420	2,200			6,342	4,300	508
			3-18-77	6.65	7.00			3,100	10.0		7,091	5,087	537
			6-2-77		6.79		4,600	3,250	14.0		7,700	5,080	990
			8-25-77	7.00		2,686		7,000	16.8	-125	6,740	4,715	659
	SL-1	32 ft (9.8 m)	7-23-76	6.80	7.06		3,452		18.0		9,400	6,730	300
			8-5-76		6.55		5,076				9,849	7,559	293
			8-31-76		7.18		1,827				10,186	8,898	308
			2-8-77	6.90									
			3-18-77	6.72	6.95			3,100	10.0		8,416	7,541	260
			6-2-77		6.85			2,900	15.0		8,400	6,038	510
			8-25-77			2,720		5,900		-123	6,538	5,746	294
G-S-7	SL-2	19 ft (5.8 m)	3-18-77	6.48	7.52			800			902	20	114
			6-2-77		7.00		380	1,080	14.5		930	16	94
	SL-1	29 ft (8.8 m)	2-8-77	6.25	7.59		330	640			558	9	137
			3-18-77	6.05	8.06			600			629	8	128
			6-2-77		7.78		290	590			700	6	110
			8-25-77	6.16		210		775		+150	537	14	116
G-S-8	SL-2	9 ft (2.7 m)	8-31-76		7.45		220				945	95	53
			3-18-77	6.66	7.40			525	8.0		714	38	32
			6-2-77		7.60			810	14.8		1,300	47	93
			8-25-77	6.72		550		1,200	19.0	-30	826	57	31

Chemical analyses of soil-moisture samples from pressure-vacuum lysimeters.

Hardness as $CaCO_3$ (mg/L)	Nitrate-N (mg/L)	Ammonia-N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Iron (total) (mg/L)	Lead (mg/L)	Magnesium (mg/L)	Manganese (mg/L)	Mercury (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Zinc (mg/L)	Comments
				800	25	< 0.1	10		< 0.2	6.5	440	0.05	Overlain by 13 ft (4 m) of refuse.
				840	24	< 0.1	10		< 0.2	6.5	480	0.17	
				800	28	< 0.1	10		< 0.2	5.0	460	0.06	
		1.5											
		2.0		64	6.1				< 0.2	0.7			
	2.3			560	60	< 0.1	10		< 0.2	5.5	480	0.01	
	2.2			840	106	< 0.1	10		< 0.2	4.0	380	0.01	
	2.4			800	94	< 0.1	10		< 0.2	4.0	400	0.01	
		0.0											
		1.0		105	84					0.9	290		
	1.9												
				1,120	26	< 0.1	20		< 0.2	10.0	1,060	0.01	
				1,800	40	< 0.1	40		< 0.2	9.0	1,060	0.01	
		< 1.0		450	71					1.8			
				1,320	88	< 0.1	30		< 0.2	10.0	520	0.04	Overlain by 17 ft (5.2 m) of refuse.
				1,680	120	< 0.1	40		< 0.2	11.5	460	0.01	
				800	28	< 0.1	10		< 0.2	5.0	460	0.06	
		11.0											(IEPA)
	4.6		< 0.01	1,900	220	< 0.1	7			5.0	160	0.03	
	< 0.1		< 0.01	533	240	< 0.01	20		< 0.2	12.5	255	0.01	
		6.0											
		10.0		363	193					2.4	236		
				1,480	151	< 0.1	40		< 0.2	17.0	1,000	0.03	
	4.4			1,720	180	< 0.1	50		< 0.2	14.5	940	0.04	
	5.6			2,120	210	< 0.1	80		< 0.2	14.0	860	0.05	
	3.9			1,700	224	< 0.1	84			5.0	395	0.03	
	0.1			660	220	< 0.1	20			11.5	860	< 0.01	
		0.0											
		0.0		341	146					1.9	840		
	5.8			2,840	136	0.1	50		< 0.2	17.0	1,260	0.10	
	7.0			3,520	208	< 0.1	120		< 0.2	15.5	1,100	0.10	
	6.8			3,760	236	< 0.1	120		< 0.2	14.0	1,000	0.12	
			< 0.01	736	176	< 0.01	20			11.0	950	0.03	
	< 0.1		< 0.01	408	234	< 0.01	20			8.5	890	0.02	
		0.0											
		1.0		354	111					1.3	870		
	0.3		178	86	15	< 0.01	20		< 0.2	1.5	53	0.10	Apparently uncontaminated.
		0.0											
	0.3		35	83	1.5	< 0.01	19			1.5	36	0.06	
	0.2		35	53	1	< 0.01	18			0.5	36	0.02	
		0.0											
		0.0											
	1.0			660	55		31		< 0.2	4.0	31	0.10	Overlain by 5 ft (1.5 m) of refuse.
	0.9												
		0.5											
		1.0		105	34.1					0.7	20		

Boring	Lysimeter	Depth	Date sampled	pH[b]	pH[c]	Alkalinity as $CaCO_3$ (mg/L)[b]	Alkalinity as $CaCO_3$ (mg/L)[c]	Specific conductivity (μmhos)[b]	Temp. (°C)[b]	Eh (mv)[b]	Total dissolved solids (mg/L)	COD (mg/L)	Chloride (mg/L)
	SL-1	23 ft (7.0 m)	8-5-76										
			8-31-76										
			6-2-77		7.94			775	14.5		1,000	22	87
			8-25-77	6.60				1,090	17.0		768	32	102
G-S-10	SL-1	30 ft (9.1 m)	6-2-77		8.10			1,100	15.0		1,500	41	121
			8-25-77	6.85		660		1,600	18.0	+28	638	41	51
SAVANNA LANDFILL													
S-S-1	SL-1	26 ft (7.9 m)	5-27-76	6.40	8.11		536		15.0		910	79	208
			2-9-77	6.85				2,000					
			3-17-77	6.60	7.02			2,100	11.0	-42	2,671	396	294
S-S-2	SL-1	24 ft (7.3 m)	9-1-76										
			3-17-77	6.80	7.36			4,500	12.0	-50	5,583	1,944	1,322
			8-25-77	7.00		440		6,200		-110	4,914	1,017	1,326
S-S-3	SL-2	9 ft (2.7 m)	2-9-77	6.75	7.11		494	850			959	4	19
			3-17-77	6.68	7.58			1,100	8.0		1,067	15	15
	SL-1	19 ft (5.8 m)	2-9-77	7.05	7.22			850	9.5		1,174	23	46
			3-17-77	6.90					5.0				
			8-24-77	6.53		175		1,940		+190	1,261	21	68
S-S-4	SL-1	34 ft (10.4 m)	7-27-76		7.16		262		24.5		1,243	18	141
			9-1-76										
			3-17-77	6.46	7.19			1,100	14.0		1,412	15	80
S-S-5	SL-1	17 ft (5.2 m)	8-24-77	6.58		500		1,225		+185	1,051	15	30
S-S-6	SL-2	12 ft (3.7 m)	2-9-77	6.70				1,400					
			3-17-77	6.50	7.06			1,275			1,278	43	78
	SL-1	22 ft (6.7 m)	2-9-77	6.55				1,200					
			3-17-77	6.45	7.16			1,130	9.0		1,209	10	10
S-S-7	SL-1	25 ft (7.6 m)	2-9-77	6.70				1,100	5.0				
			3-17-77	6.46	6.97			1,170	10.0	0	1,293	53	14
CRYSTAL LAKE													
CL-S-3	SL-3	9 ft (2.7 m)	6-23-76		7.06		441				1,973	88	42
			8-30-76		6.80		880				1,610	82	80
			1-4-77	6.50	7.23		960		16.0		1,064	51	43
			3-15-77	6.70	7.57			1,250	8.0	+145	1,553	43	39
			8-22-77	7.02		880		2,100	21.0	+145	1,558	27	75
	SL-2	21 ft (6.4 m)	6-23-76		7.28		349				619	13	152
			8-30-76		7.60			1,742				16	70
			1-4-77										
			3-15-77	6.72	6.99			850	11.0	+167	1,473	32	31
			8-22-77	6.95		684		1,550	19.2	+178	1,089	10	39
	SL-1	37 ft (11.3 m)	6-23-76										
			8-30-76		7.10		200				730	12	23
			3-15-77	6.70	7.76			700	11.0	+179	838	6	16
			8-22-77	7.14		581		1,100	18.0	+185	806	5	31

Chemical analyses of soil-moisture samples from pressure-vacuum lysimeters *(continued)*.

Hardness as $CaCO_3$ (mg/L)	Nitrate-N (mg/L)	Ammonia-N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Iron (total) (mg/L)	Lead (mg/L)	Magnesium (mg/L)	Manganese (mg/L)	Mercury (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Zinc (mg/L)	Comments
				660	1.2	< 0.10	35		< 0.2	4.0	34	0.02	
				600	0.6	< 0.10	42		< 0.2	3.0	18	0.08	
		0.0											
		0.0		83	6.1					0.4	180		
		0.0											
		0.0		141	21.0					1.3	39		Overlain by 5 ft (1.5 m) of refuse.
	1.2			756	1.65	< 0.10	77		< 0.2	6.5	140	0.21	Overlain by 16 ft (4.9 m) of refuse.
			78	318	76.0	< 0.01	20			6.0		0.01	
	2.0		65	440	85.0	< 0.01	20		< 0.2	5.5	430	0.01	
				5,600	450.0	0.10	160		< 0.2	24.0	820	0.90	
	0.7		6	2,320	63.0	< 0.01	900		< 0.2	85.0	400	0.01	
		240											
	115.0		245	193	0.1	< 0.01	19			3.0	17	0.17	
	172.0		245	119	0.2	< 0.01	19			1.5	10	0.24	
	33.0								< 0.2				
			120	126	0.1	< 0.01	19		< 0.2	1.5	22	0.01	
		0.0		268									
	1.1			870	1.7	< 0.10	56		< 0.2	5.0	33	0.36	
				834	0.95	< 0.10	60		< 0.2	4.0	22	0.21	
	0.4			276	4.1	< 0.01	20		< 0.2	3.5	17	0.16	
		0.0		217									
			82	158	60.0	< 0.01	20			7.5	5	0.01	
	1.6		63	154	67.0	< 0.01	20		< 0.2	6.5	47	< 0.01	
			53	144	2.3	< 0.01	20			3.0	33	0.01	
	0.4		58	171	3.9	< 0.01	20		< 0.2	2.5	31	< 0.01	
			0.01	144	8.5	< 0.01	20			1.5	18	0.01	
	0.6		21	137	31.0	< 0.01	20		< 0.2	1.0	17	0.02	
	2.6			694	4.0	< 0.10	48		< 0.2	14.5	69	0.05	
		13.0		180	85.0	0.00	93	0.58	0.0	8.0	115		
	2.3		64	99	24.0	< 0.01	20			45.0	93	0.03	
	38.0		250	122	2.3	< 0.01	20			46.0	105	0.20	
		1.0		246									
	3.5			740	0.1	< 0.10	49		< 0.2	9.0	220	0.01	
		0.0	190	170	0.0	0.00	55	0.53	0.0	8.2	145		(IEPA)
			78	130	0.15	< 0.01	20			0.5	9	0.12	
	14 0		197	118	0.2	< 0.01	20		< 0.2	3.0	6.7	0.24	
		0.0		243									
				522	0.05	< 0.10	46		< 0.2	2.0	22	0.05	
650			80	130	0.0	0.00	55	0.12	0.0	2.8	15		(IEPA)
	4.7		73	96	0.15	< 0.01	20			0.5	6.5	0.17	
		0.0		268									

Boring	Lysimeter	Depth	Date sampled	pH[b]	pH[c]	Alkalinity as $CaCO_3$ (mg/L)[b]	Alkalinity as $CaCO_3$ (mg/L)[c]	Specific conductivity (μmhos)[b]	Temp. (°C)[b]	Eh (mv)[b]	Total dissolved solids (mg/L)	COD (mg/L)	Chloride (mg/L)
CL-S-4	SL-1	11 ft (3.4 m)	8-30-76		6.84		347				1,004	19	25
			3-15-77	6.35	7.39			950	6.0	+165	1,099	17	25
			8-22-77	7.00		642		1,510	21.8	+90	1,107		27
CL-S-5	SL-1	34 ft (10.4 m)	8-30-76										
			3-15-77	6.48	7.68			1,100	15.0	+181	1,410	80	116
			8-22-77	7.40		615			22.5	+118	795	440	64
CL-S-7	SL-1	30 ft (9.1 m)	8-30-76		7.42		344				3,172	272	749
			3-15-77	6.35	7.54			2,000	15.0	+165	3,191	88	21
			8-22-77	6.98		940		3,400	22.5	-52	3,664	921	1,117

[a]Analyses by the Illinois State Geological Survey unless noted otherwise.
[b]Field analyses upon sample collection.
[c]Laboratory recheck.

Chemical analyses of soil-moisture samples from pressure-vacuum lysimeters *(continued)*.

Hardness as $CaCO_3$ (mg/L)	Nitrate-N (mg/L)	Ammonia-N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Iron (total) (mg/L)	Lead (mg/L)	Magnesium (mg/L)	Manganese (mg/L)	Mercury (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Zinc (mg/L)	Comments
	0.3			776	0.25	< 0.10	49		< 0.2	3.0	12	0.08	
	0.9		130	126	1.5	< 0.10	19		< 0.2	4.0	10	0.17	
		0.0		246									
				1,720	0.65	< 0.10	50		0.2	6.0	200	0.04	Overlain by 25 ft (7.6 m) of refuse.
	17.0												
		0.0											
	4.5												Overlain by 25 ft (7.6 m) of refuse.
	1.0												
		0.0											

APPENDIX 6.

Laboratory methods for chemical analyses of water and soil samples.

A. WATER SAMPLES

Parameter	Method
Alkalinity (as $CaCO_3$)	Potentiometric titration
Chloride (Cl)	Mercurimetric titration; specific ion electrode
Chemical oxygen demand (COD)	*Standard methods,* 1971
Ammonia (NH_4-N)	Nesslerization
Nitrate (NO_3-N)	Phenoldisulfonic acid
pH	Glass electrode
Specific conductivity (SC)	Conductivity bridge
Sulfate (SO_4)	Turbidimetric
Total dissolved solids (TDS)	Evaporation
Hardness (as $CaCO_3$)	EDTA
Oxidation-reduction potential (Eh)	Pt-Calomel electrode, Orion meter
Calcium (Ca)	Atomic absorption (AA)
Total iron (Fe)	AA
Lead (Pb)	AA
Magnesium (Mg)	AA
Manganese (Mn)	AA
Mercury (hg)	AA
Potassium (K)	AA
Sodium (Na)	AA
Zinc (Zn)	AA

B. SOIL SAMPLES

Parameter	Method
Calcium (Ca)	X-ray fluorescence (XRF)
Magnesium (Mg)	XRF
Total iron (Fe)	XRF
Potassium (K)	XRF
Sodium (Na)	Neutron activation (NA)
Lead (Pb)	Atomic absorption (AA)
Mercury (Hg)	NA
Zinc (Zn)	AA
Chloride (Cl)	Gravimetric
Sulfate (SO_4)	Gravimetric
Total carbon (C)	Heating
Cation exchange capacity (CEC)	*Standard methods,* 1971
pH	1:1 distilled water-soil mixture

APPENDIX 7.

Descriptive logs of soil samples from borings.

GENESEO LANDFILL

Boring G-S-1	Depth (ft)	(m)
Cover—sand, medium grained	0-2	0-.6
Refuse—wood, glass, metal, paper (wet)	2-16.5	.6-5
Sand, fine to medium, brown	16.5-22.5	5-6.9
Silt, sandy, clayey	22.5-23.5	6.9-7.2
Sand, fine, silty, brown	23.5-29	7.2-8.8
Till, silty clay, brown	29-30	8.8-9.2
Sand, brown, silty	30-31	9.2-9.5
Till, clayey, silty, gray-brown	31-35	9.5-10.7
Sand, medium, brown	35-36	10.7-11.0
Boring G-S-3		
Cover—sand, medium grained	0-2	0-.6
Refuse—metal, wood, paper, glass	2-12.5	.6-3.8
Sand, fine to medium, brown	12.5-20	3.8-6.1
Silt, sandy, clayey, brown	20-22	6.1-6.7
Sand, trace silt, brown	22-29.5	6.7-9.0
Sand, fine, silty brown; gray silt lense at 31 ft (9.5 m)	29.5-31.5	9.0-9.6
Sand, fine to medium, brown	31.5-32.5	9.6-9.9
Till, silty clay, sandy, green-brown to gray-brown	32.5-35	9.9-10.7
Sand, pebbly, silty, brown wet	35-35.5	10.7-10.8
Till, silty clay, sandy, brown	35.5-37	10.8-11.3
Boring G-S-7		
Sand (no samples)	0-30	0-9.2
Silt, clayey, sandy, gray	30-31	9.2-9.5
Sand, silty, gray to black, leachate odor	31-35	9.5-10.7
Sand, medium, brown	35-37	10.7-11.3
Boring G-S-8		
Cover—sand, silty	0-2	0-.6
Silt, sandy, clayey (soil)	2-4	.6-1.2
Fill—mixed sandy silt and refuse, gray, leachate odor	4-13	1.2-4.0
Sand, medium, brown (no samples)	13-25	4.0-7.6
Boring G-S-10		
Fill (not refuse)—sand, black	0-3.5	0-1.1
Sand, fine, silty, brown	3.5-4.5	1.1-1.4
Silt, sandy, gray-brown	4.5-6.5	1.4-2.0
Silt, clayey, brown	6.5-7.5	2.0-2.3
Sand, fine, brown	7.5-21	2.3-6.4
Silt, clayey, sandy, gray to gray-brown, wood fragments	21-23	6.4-7.0
Sand, silty, brown to gray-brown	23-24.5	7.0-7.5
Sand, fine to medium, brown	24.5-34	7.5-10.4
Silt, sandy, clayey, brown-gray	34-35	10.4-10.7
Sand, fine to medium, brown	35-36.5	10.7-11.1
Till, silty clay, gray-brown, upper portion washed	36.5-38	11.1-11.6

Descriptive logs of soil samples from borings *(continued)*.

GENESEO LANDFILL

Boring G-P-4	Depth (ft)	Depth (m)
Sand, fine to medium, brown	0-11	0-3.4
Sand, silty, brown	11-11.5	3.4-3.5
Sand, fine, trace silt, brown	11.5-25	3.5-7.6
Silt, clayey, trace sand, brown	25-27	7.6-8.2
Sand, fine to medium, silty	27-29	8.2-8.8
Silt, trace sand and clay, brown	29-31	8.8-9.5
Sand, fine to medium, silty, brown	31-36	9.5-11.0
Silt, trace clay and sand, gray-brown	36-37.5	11.0-11.4
Till, silty clay, sandy, gray-brown	37.5-48	11.4-14.6
Silt, trace clay and sand, brown-gray, wet	48-50.5	14.6-15.4
Sand, fine to medium, brown	50.5-58	15.4-17.7
Silt, clayey, gray-brown, wet	58-60.5	17.7-18.4
Sand, coarse, trace silt, brown, wet	60.5-63.5	18.4-19.4
Boring G-P-5		
Fill (not refuse)—sandy silt	0-5	0-1.5
Silt, sandy, gray-black	5-8	1.5-2.4
Sand, trace silt and clay, brown	8-10	2.4-3.0
Sand, silty brown (no samples)	10-11	3.0-3.4
Silt, clayey, gray-brown, wet	11-16.5	3.4-5.0
Sand, medium to coarse; wet; thin silt lenses	16.5-27	5.0-8.2
Boring G-P-6		
Refuse—black, wet, leachate odor	0-15	0-4.6
Sand, fine to medium, brown	15-26	4.6-7.9
Sand, medium, trace silt, gray, wet	26-28	7.9-8.5
Till, silty clay, brown	28-31	8.5-9.5
Sand, medium to coarse, gray-brown	31-32.5	9.5-9.9
Silt, trace sand and clay, gray-brown	32.5-33.5	9.9-10.2
Sand, silty, to coarse sand, with irregular beds of silt	33.5-38.5	10.2-11.7
Sand, medium to coarse, trace silt, brown, wet	38.5-42	11.7-12.8
Boring P-G-9		
Silt, clayey, organic, black	0-5	0-1.5
Silt, clayey, brown	5-10	1.5-3.0
Clay, silty, brown	10-16	3.0-4.9
Silt, massive, gray	16-17	4.9-5.2
Till, silty clay	17-19.5	5.2-5.9
Sand (not sampled)	19.5-40	5.9-12.2
Sand and gravel, coarse, brown, wet	40-42	12.2-12.8
Boring G-P-15		
Sand, fine to medium, brown	0-35	0-10.7
Till, silty clay, sandy, yellow-brown to brown	35-45	10.7-13.7
Till, silty clay, sandy, gray, few small pebbles	45-58	13.7-17.7
Silt, sandy, gray-brown	58-71	17.7-21.6
Till, silty clay, gray	71-72	21.6-22.0
Sand and gravel, medium to coarse, brown, wet	72-81	22.5-24.7
Sand, fine, silty, gray, wet	81-85	24.7-25.9
Bedrock?—refusal (no samples)	85+	25.9+

Descriptive logs of soil samples from borings *(continued)*.

GENESEO LANDFILL Boring G-B-11 *(continued)*	Depth (ft)	Depth (m)
Sand, fine to medium, brown to gray-brown	0-26	0-7.9
Sand, fine, silty, brown to gray-brown	26-30	7.9-9.1
Till, silty clay, brown	30-33	9.1-10.1
SAVANNA LANDFILL		
Boring S-S-1		
Refuse—metal, wood, paper	0-17.5	0-5.3
Sand, fine to medium; silty at 24 ft (7.3 m), brown	17.5-28	5.3-8.5
Silt, sandy, clayey, brown	28-30	8.5-9.1
Sand, medium to coarse, occasionally pebbly, brown	30-37	9.1-11.3
Sand, medium, clayey, silty, pebbly, brown	37-39	11.3-11.9
Sand, coarse, pebbly, clean, brown, wet	39-44	11.9-13.4
Boring S-S-2		
Refuse—metal, paper, garbage, gray, wet	0-25	0-7.6
Borings S-S-3		
Sand, fine to medium, brown (no samples)	0-20	0-6.1
Boring S-S-4		
Sand, medium to coarse, brown	0-9	0-2.7
Boring S-S-5		
Sand, fine to medium, brown (no samples)	0-20	0-6.1
Boring S-S-6		
Sand, medium, brown (no samples)	0-18	0-5.5
Sand, silty, gray-brown (no samples)	18-19?	5.5-5.8
Sand, medium, brown (no samples)	19-23	5.8-7.0
Boring S-S-7		
Sand, fine to medium, brown; silty at 3.7 m (12 ft) (no samples)	0-25	0-7.6
Boring S-P-4		
Sand, medium to coarse, few pebbles, brown	0-15	0-4.6
Sand and gravel, medium to coarse, brown; 19 ft (5.8 m)	15-30	4.6-9.1
Silt, clayey, locally sandy, brown, wet (no samples of lower 12 ft [3.7 m])	30-45?	9.1-13.7?
Silt, clayey to silty clay, and silty sand, reddish-brown to gray	45-52	13.7-15.8
Borings S-P-5 and S-P-6		
Sand, medium to coarse, brown (silt and silty sand lenses at 8 ft [2.4 m] and 10 ft [3 m])	0-17	0-5.2
Pebbly sand, medium to coarse, silty, brown; wet at 25 ft (7.6 m)	17-36	5.2-11.0

Descriptive logs of soil samples from borings *(continued)*.

CRYSTAL LAKE LANDFILL

Boring CL-S-3	Depth (ft)	Depth (m)
Fill (not refuse)—sand and gravel, till	0-12.5	0-3.8
Sand, very fine, silty, to sandy silt; brown (no samples)	12.5-37	3.8-11.3
Boring CL-S-4		
Fill (not refuse)—sand and gravel	0-8	0-2.4
Sand, very fine, silty, brown (no samples)	8-12	2.4-3.7
Borings CL-S-5 and CL-S-7		
Refuse—paper, metal, garbage; wet	0-25	0-7.6
Sand and gravel; sandy till; silty, clayey, gray-brown to brown (liner)	25-27	7.6-8.2
Bentonite clay layer (liner)	27-27.1	8.20-8.24
Sand, very fine, silty, to medium brown	27.1-35	8.24-10.7
Boring CL-P-6		
Fill (not refuse)—sand and gravel (no samples)	0-5	0-1.5
Sand, very fine, silty, to silt, brown; wet at 35.5 ft (10.8 m); sandy near base	5-40	1.5-12.2
Boring CL-P-11		
Fill (not refuse)—sand and gravel, glacial till	0-8	0-2.4
Sand and gravel, medium to coarse, brown	8-13.5	2.4-4.1
Sand, very fine, silty to sandy silt, brown; wet at 41 ft (12.5 m); sandy near base	13.5-50	4.1-15.2
Boring CL-P-12		
Refuse—paper, wood, metal; wet	0-25	0-7.6
Sand and gravel, silty, clayey; glacial till; thin bentonite layer (0.4 in. [1 cm]) at base (liner)	25-27.5	7.6-8.4

APPENDIX 8.

Texture and clay mineralogy of soil samples.

Boring	Depth (ft)	Material	W[a] (%)	Texture[b] Gvl (%)	Sd (%)	Si (%)	Cl (%)	Clay mineralogy[c] Ex (%)	I (%)	C + K (%)
GENESEO LANDFILL										
G-S-1	16.5-17.0	Sand	3.1	0	96	0	4			
Elev. 657.8 ft	17.0-17.5	Sand		0	87	6	7			
(200.49 m)	17.5-18.0	Sand		0	95	1	4			
	18.0-18.5	Sand	3.5	0	94	1	5			
	18.5-19.0	Sand		0	95	1	4			
	19.0-20.1	Sand		0	93	1	6			
	20.1-21.0	Sand		0	94	1	5			
	21.0-21.8	Sand	6.2	0	91	2	7			
	22.0-22.5	Sand		0	95	1	4			
	22.5-22.7	Sandy silt	29.9	0	26	55	20	55	30	15
	23.0-23.5	Clayey silt	14.3	0	12	58	30	62	26	12
	23.5-24.0	Sand	4.6	0	91	1	8			
	24.0-25.8	Sand		0	80	10	10			
	25.8-26.5	Sand		1	89	6	5			
	26.5-27.3	Sand		0	85	8	7			
	27.3-27.7	Sandy silt		0	25	71	4	72	19	9
	27.7-27.8	Silty sand		0	81	13	6			
	28.0-29.0	Silty sand		0	82	9	9			
	29.0-29.5	Silty sand		0	74	18	8	25	62	12
	31.0-31.8	Clay till		1	6	28	66	9	81	10
	31.8-32.5	Clay till		0	2	23	75	6	82	12
	32.5-33.0	Clay till	21.4	0	5	40	55	8	77	15
	34.6-35.0	Silty clay till		1	23	25	52	13	73	14
	35.0-36.0	Sand		0	93	2	5			
G-S-3	16.0-16.9	Sand		0	93	1	6			
Elev. 670.5 ft	19.5-20.2	Silty sand		0	64	30	6			
(204.36 m)	20.2-20.9	Silt		0	15	70	16			
	20.9-21.5	Sandy silt		0	23	69	9			
	24.5-25.9	Sand		0	89	5	6			
	25.9-26.5	Sand		0	88	11	2			
	26.5-27.5	Sand		0	87	7	6			
	27.5-28.5	Sand		0	89	5	6			
	29.5-30.2	Silty sand		0	83	13	4			
	30.2-30.9	Silty sand		0	76	17	7			
	30.9-31.2	Silt		0	14	70	16	61	29	10
	31.2-31.5	Sand		0	86	3	11			
	31.5-32.2	Sand		0	90	4	6			
	32.2-32.8	Sand	7.2	0	96	5	9			
	32.8-33.5	Silty clay till		1	21	40	40	3	82	15
	33.5-33.9	Silty clay till		1	25	33	42	3	77	20
	33.9-34.2	Silty clay till		5	19	39	43	4	81	15
	34.2-34.8	Silty clay till		5	24	40	37	4	84	12
	34.9-35.1	Silty clay till		11	36	38	26	2	77	21
	35.1-35.4	Pebbly silt	16.3	27	11	69	20	2	78	20
	35.4-35.5	Silty clay till		6	26	45	29	3	79	18
	35.0-35.3	Silty clay till	19.2				38	5	83	12
	35.3-35.9	Silty clay till		5	20	40	39			
	35.9-36.0	Silty clay till		5	21	43	35	5	84	11
	36.0-36.5	Silty clay till		5	21	41	37	4	83	13
	36.5-37.0	Silty clay till								
G-S-7	30.0-31.0	Silt		0	14	60	27	63	24	13
Elev. 673.3 ft	34.5-35.0	Sand		0	85	10	5			
(205.21 m)	35.0-36.0	Sand		0	96	0	4			
G-S-8	10.0-11.0	Sandy silt		0	31	49	20	56	31	13
Elev. 674.1 ft										
(205.46 m)										

Texture and clay mineralogy of soil samples *(continued)*.

Boring	Depth (ft)	Material	W[a] (%)	Texture[b] Gvl (%)	Sd (%)	Si (%)	Cl (%)	Clay mineralogy[c] Ex (%)	I (%)	C + K (%)
GENESEO LANDFILL										
G-S-10	3.5-4.5	Silty sand		0	41	41	18			
Elev.-674.1 ft	4.5-4.6	Silty sand		0	43	37	20			
(205.46 m)	4.6-4.7	Sandy silt		0	36	43	21			
	5.0-5.5	Silt		0	15	63	22			
	6.0-6.1	Silt		0	10	67	23			
	6.1-6.5	Sandy silt		0	38	44	19			
	6.5-7.0	Silt		0	8	70	23			
	7.5-7.8	Silt		0	4	75	21			
	7.8-8.0	Silt		0	5	70	25			
	8.0-8.5	Sand		0	87	5	8			
	8.5-9.0	Sand		0	94	1	7			
	9.0-9.5	Sand		0	93	1	6			
	10.0-10.5	Sandy silt		0	18	60	22			
	11.0-11.5	Sand		0	80	10	10			
	11.5-13.0	Sand		0	95	1	4			
	15.0-16.5	Sand		0	96	0	4			
	20.0-21.0	Sand		0	88	6	6			
	21.0-21.3	Sandy silt		0	26	58	16	52	35	13
	21.7-21.9	Clayey silt		0	4	61	36	69	21	10
	21.9-22.0	Silt		0	16	62	22	72	22	6
	22.0-22.5	Silt						68	23	9
	23.0-23.5	Sandy silt		0	25	59	16			
	23.5-24.5	Sandy silt		0	46	46	8			
	31.5-32.0	Sand		0	87	9	4			
	33.5-34.0	Sand		0	93	5	2			
	34.5-34.7	Sandy silt		0	17	68	15	68	21	11
	35.0-35.5	Sandy silt		0	26	61	13	72	20	8
	36.0-36.5	Sand		0	90	5	5			
	36.5-36.7	Sand		0	93	2	5			
	37.0-37.2	Silty clay till		7	17	46	38	27	62	11
	37.3-37.5	Silty clay till						4	85	11
	38.0-38.5	Silty clay till		7	18	45	38	4	84	12
G-P-4	7.0-7.5	Sand	11.5	0	91	1	8			
Elev.-674.3 ft	10.7-11.2	Silty sand	18.9	0	83	15	2	55	33	12
(205.52 m)	12.2-13.0	Silty sand	9.8	0	49	39	12			
	19.3-20.0	Sand	2.7	0	87	7	6			
	23.5-24.5	Sand	2.7	0	89	6	5			
	26.0-26.6	Clayey silt	22.6	0	9	69	22	74	18	8
	27.0-28.0	Silty sand	6.5	0	75	19	6			
	30.5-31.0	Silt	22.0	0	12	74	15	61	26	13
	32.0-33.5	Silty sand	4.4	0	87	11	2			
	36.2-36.8	Silt	22.2	0	10	72	17	65	25	10
	38.0-38.5	Silty clay till	13.4	9	23	42	35	6	84	10
	40.6-41.2	Silty clay till	15.3	9	29	27	44	7	82	11
	42.5-43.1	Silty clay till	15.0	2	22	41	37			
	47.3-47.9	Silty clay till	12.2	5	20	46	34	2	77	21
	48.3-49.0	Silt	20.3	0	6	85	14	8	67	25
	58.3-59.0	Silt	24.7	0	2	88	11	8	69	23
G-P-5	8.0-8.5	Sand	14.6	0	91	3	6			
Elev.-633.2 ft	13.0-13.5	Silt	34.1	0	2	84	14			
(192.99 m)	15.7-16.5	Clayey silt	24.5	0	1	60	39	8	83	9
	17.0-18.0	Sand		0	93	6	1			
	20.0-21.0	Sand	14.9	0	82	10	8			
	26.0-27.0	Sand	21.7	0	95	3	2			

Texture and clay mineralogy of soil samples *(continued)*.

Boring	Depth (ft)	Material	W[a] (%)	Texture[b] Gvl (%)	Sd (%)	Si (%)	Cl (%)	Clay mineralogy[c] Ex (%)	I (%)	C + K (%)
GENESEO LANDFILL										
G-P-6	15.0-15.5	Sand	20.0	0	86	1	13			
Elev.-652.05 ft	16.5-17.0	Sand	4.0	0	91	7	2			
(192.99 m)	20.0-21.0	Sand		0	89	6	5			
	22.0-23.0	Sand		0	82	13	5			
	26.0-27.0	Sand	15.9	0	85	10	5			
	28.0-28.5	Sandy clay till	16.7	0	36	19	45	21	69	10
	30.5-31.0	Silty clay till		0	6	34	60	28	63	9
	31.0-32.0	Sand	3.7	0	89	5	6			
	32.5-33.0	Silt	25.6	0	7	86	7			
	33.5-34.0	Sand		5	88	4	8			
	34.0-35.5	Silty sand		0	63	30	7			
	35.5-36.5	Sand	7.1	0	94	2	8			
	37.5-38.0	Sandy silt		0	31	40	29	18	67	16
	38.5-40.0	Sand		0	84	8	8			
	40.7-42.0	Sand	18.8	0	98	0	2			
G-P-9	6.0-6.5	Clayey silt		0	4	69	27			
Elev.-645.0 ft	10.0-10.2	Silt						62	30	8
(196.59 m)	10.2-10.5	Silty clay						26	67	7
	11.0-11.1	Silty clay		0	1	21	78	42	49	9
	12.0-12.2	Silty clay		0	2	26	72	36	54	10
	12.5-13.0	Silty clay						52	38	10
	13.0-13.6	Silty clay		1	3	23	73	26	67	7
	14.0-14.5	Silty clay						50	42	8
	15.0-15.2	Silty clay						41	53	6
	15.5-15.9	Silty clay		0	12	32	56	40	50	10
	16.0-16.3	Silty clay		0	2	29	70	21	68	11
	16.3-16.4	Silty clay		0	0	22	78	23	64	13
	16.4-16.5	Silt						18	65	17
	16.5-16.9	Silty clay		0	1	28	71	22	68	10
	17.0-17.3	Silty clay till		2	10	36	53	23	68	9
	18.0-18.2	Silty clay till						24	67	9
	18.2-18.7	Silty clay till		0	7	33	60	17	73	10
	19.0-19.5	Silty clay till						18	72	10
G-P-15	35.5-35.8	Silty clay till						7	80	13
Elev.-675.0 ft	35.8-36.0	Silty clay till		3	20	53	27	5	83	12
(205.73 m)	36.0-36.7	Silty clay till		7	37	22	41	6	81	13
	40.5-40.8	Silty clay till		3	34	29	37	7	81	12
	40.8-41.2	Silty clay till		21	34	37	29	6	82	12
	41.4-41.8	Silty clay till		9	28	37	34	5	81	14
	45.6-46.0	Silty clay till		7	28	37	34	4	80	16
	46.0-47.0	Silty clay till		3	21	58	21	3	75	22
	50.5-51.0	Silty clay till		9	27	39	34	3	73	24
	51.0-51.7	Silty clay till		5	35	32	33	5	74	21
	55.5-56.0	Silty clay till		2	19	50	31	3	75	22
	56.0-57.0	Silty clay till		5	29	42	29	4	73	23
	60.5-61.8	Sandy silt		0	10	83	6	5	62	33
	61.3-62.0	Sandy silt		8	37	41	22	8	64	28
	65.5-66.3	Sandy silt		0	20	73	7	9	61	30
	66.3-67.0	Sandy silt		0	7	84	9	17	60	23
	70.8-71.7	Silty till (?)		3	6	31	63	16	65	19
	75.5-76.2	Sandy silt						8	67	25
	80.4-81.3	Sandy silt						6	66	28
	81.3-82.0	Sandy silt		0	44	47	8	8	63	29

APPENDIX 8.

Texture and clay mineralogy of soil samples *(continued)*.

Boring	Depth (ft)	Material	W[a] (%)	Texture[b] Gvl (%)	Sd (%)	Si (%)	Cl (%)	Clay mineralogy[c] Ex (%)	I (%)	C + K (%)
GENESEO LANDFILL										
G-B-11	30.0-30.3	Clayey silt		2	0	61	39	5	85	10
Elev.-675.0 ft	31.0-31.2	Silty clay till		2	21	37	43	4	87	9
(205.73 m)	32.0-32.1	Pebbly silt		16	15	61	25	3	86	11
	32.5-32.7	Sandy clay till		3	57	7	35	3	86	11
SAVANNA LANDFILL										
S-S-1	20.5-21.0	Sand	4.9	0	89	5	6			
Elev.-125.0 ft	21.5-22.0	Sand		0	90	6	4			
(38.10 m)	22.5-23.0	Sand	7.3	0	86	6	8			
	23.2-23.7	Sand		0	83	10	7			
	23.7-24.1	Silty sand	23.2	0	38	43	19			
	24.1-24.7	Silty sand	19.0	0	37	57	7			
	25.3-25.7	Sand	4.0							
	25.7-26.0	Sand		0	97	1	2			
	26.0-26.3	Silty sand	27.4	0	35	50	15	64	20	14
	26.3-27.3	Sand		0	94	3	3			
	28.0-28.3	Sandy silt	32.9	0	28	56	16			
	28.5-29.0	Sandy silt	28.2	0	14	71	15	63	22	14
	29.0-29.3	Sandy silt		0	12	80	8			
	29.5-30.0	Sandy silt		0	21	60	19	67	20	13
	30.0-30.5	Sand		0	87	9	4			
	30.5-31.0	Sand	17.4	0	81	17	2			
	32.0-32.5	Sand	3.8	18	97	1	2			
	35.0-35.5	Sand	6.4	0	98	1	1			
	35.8-36.7	Sand		1	88	10	2			
	37.3-37.5	Sand	23.5	3	77	5	17			
	37.5-37.7	Silty sand	31.9	12	55	21	24			
	37.7-38.0	Silty sand		7	59	14	27			
	38.0-39.0	Sand		7	81	4	15			
	40.7-41.2	Pebbly sand	4.7	29	98	1	1			
	41.2-41.7	Pebbly sand	7.9	27	98	1	1			
	43.0-43.5	Pebbly sand	13.3	16	95	0	5			
	43.5-44.0	Pebbly sand		8	98	1	1			
S-S-4	2.0-2.5	Sand		2	92	6	2			
Elev.-95.0 ft	3.0-3.5	Silty sand		0	51	45	4			
(28.95 m)	5.0-5.5	Sand		0	98	1	1			
	9.0-9.5	Sand		10	95	3	2			
S-P-4	5.0-5.5	Sand		1	93	3	4			
Elev.-109.71 ft	10.5-11.5	Sand	3.4	0	98	1	1			
(33.44 m)	11.5-12.3	Sand	4.4	3	97	1	2			
	13.5-14.5	Sand	3.1	3	97	2	1			
	14.5-15.0	Sand		1	94	1	5			
	15.5-16.0	Pebbly sand	3.4	9	97	2	1			
	16.5-17.0	Pebbly sand		4	97	2	1			
	18.0-19.0	Pebbly sand	5.8	9	96	0	4			
	20.0-20.5	Pebbly sand	15.1	17	97	1	2			
	21.0-21.5	Pebbly sand		14	86	6	8			
	35.0-35.5	Clayey silt	28.0	0	4	82	13			
	35.5-36.0	Clayey silt		1	5	77	18			
	36.0-36.5	Clayey silt		0	1	81	18			
	36.5-37.0	Clayey silt	27.1	0	4	79	17			
	37.0-37.7	Sandy silt	18.3	0	38	47	15			
	37.7-37.8	Clayey silt		0	16	65	18			
	38.0-39.0	Clayey silt	23.2	0	7	71	22			

APPENDIX 8.

Texture and clay mineralogy of soil samples *(continued)*.

Boring	Depth (ft)	Material	W[a] (%)	Texture[b] Gvl (%)	Sd (%)	Si (%)	Cl (%)	Clay mineralogy[c] Ex (%)	I (%)	C + K (%)
SAVANNA LANDFILL										
S-P-4 *(continued)*	49.5-50.0	Clayey silt	23.2	1	19	14	67			
Elev.-109.71 ft	50.0-50.2	Clayey silt	24.2	0	19	71	10			
(33.44 m)	50.2-50.4	Clayey silt	22.6	0	9	70	21			
	50.4-51.0	Clayey silt	21.2	0	24	58	18			
	51.0-51.5	Clayey silt		0	2	55	43			
	51.5-51.8	Clayey silt		1	9	70	21			
S-P-5	5.0-6.0	Sand	6.0	0	95	3	2			
Elev.-117.22 ft	7.0-8.0	Sand		0	98	0	2			
(35.73 m)	8.0-8.5	Sandy silt	20.1	0	20	65	15	59	23	17
	8.5-9.0	Silty sand		0	82	14	4			
	10.0-10.5	Silty sand	28.8	0	64	12	24	65	24	10
	10.5-12.0	Sand		0	91	4	5			
	12.0-13.0	Silt		0	2	96	2			
	16.0-17.0	Sand		0	94	4	2			
	17.0-18.5	Sand		6	80	20	0			
	20.0-21.0	Sand		8	93	2	5			
	21.0-22.0	Pebbly sand		27	90	4	6			
	23.0-23.5	Pebbly sand		5	96	1	3			
	25.5-26.5	Pebbly sand		14	90	4	6			
	34.0-35.0	Silty sand	2.9	23	68	24	7			
CRYSTAL LAKE LANDFILL										
CL-P-6	11.2-12.0	Sandy silt		0	43	56	1			
Elev.-884.51 ft	16.0-17.0	Silt	5.8	0	4	89	7			
(269.59 m)	20.0-21.0	Silt	17.9	0	1	94	5			
	23.0-23.2	Sandy silt	18.3	0	47	50	3			
	26.0-27.0	Sandy silt	6.0	0	30	63	7			
	31.0-32.0	Silt		0	14	77	9			
	35.3-35.6	Silt	20.0	0	8	89	2			
	36.0-37.0	Sandy silt	20.2	0	16	76	9			
	38.0-39.0	Sandy silt	17.5	0	33	65	2			
CL-P-11	9.5-10.0	Haeger till		29	38	38	24			
Elev.-889.7 ft	11.0-11.5	Sand and gravel		29	84	7	9			
(271.17 m)	12.0-12.5	Sand and gravel		20	93	3	9			
	15.0-15.5	Sand		0	87	7	6			
	16.5-17.0	Silty sand		0	59	35	6			
	23.0-23.5	Sandy silt		0	36	55	8			
	25.5-26.0	Sandy silt		0	15	76	10			
	31.5-32.0	Sandy silt		0	33	61	6			
	35.5-36.0	Sandy silt		0	37	58	5			
	38.5-39.0	Silty sand		0	52	41	7			
	40.0-40.5	Sandy silt		0	41	55	4			
	41.5-42.0	Sandy silt		0	30	60	10			
Spoil Bank	3.0-3.5	Soil (B-horizon)						46	39	15
50 ft (15.2 m)	4.0-4.5	Soil (B-horizon)						43	38	19
north of fill (used as liner)	5.0-5.5	Haeger till						12	67	21

[a] Gravimetric water content.
[b] Gravel >2 mm; sand 2-0.062 mm; silt 0.062-0.0039 mm; clay <0.0039 mm.
[c] Ex = Expandables; I = Illite; C + K = Chlorite plus Kaolinite.
[d] Elevations at Savanna above arbitrary datum.

APPENDIX 9.

Hydraulic conductivity data from laboratory tests.[a]

Boring	Sample depth (ft)	Material	Hydraulic conductivity (cm/sec)[b]	Comments
GENESEO LANDFILL				
S-1	24.0-25.8	Sand	1.9×10^{-3}	9 ft (2.7 m) below refuse
S-3	27.8-28.5	Sand	6.3×10^{-4}	15 ft (4.6 m) below refuse
S-3	33.5-33.9	Silty clay till	4.5×10^{-8}	Measured porosity = 29%
P-4	30.5-31.0	Sandy, clayey silt	5.2×10^{-6}	
P-4	35.0-36.2	Silty sand	3.0×10^{-3}	
P-4	38.5-39.0	Silty clay till	2.5×10^{-8}	
P-5	13.0-13.5	Silt	3.8×10^{-6}	500 ft (152 m) east of fill
SAVANNA LANDFILL				
S-1	31.0-32.0	Pebbly sand	7.6×10^{-4}	15 ft (4.6 m) below refuse
P-4	8.0-8.5	Sand	2.0×10^{-3}	
P-5	16.0-17.0	Sand	1.9×10^{-3}	
CRYSTAL LAKE LANDFILL				
S-7	25.6-26.3	Silty, sandy till with 3/8 in. bentonite	6.6×10^{-7}	Liner beneath refuse
S-7	26.5-27.0	Silty sand	2.3×10^{-6}	Sand below liner
P-6	31.0-32.0	Sandy silt	1.5×10^{-4}	

[a] Values obtained by variable head test using Soiltest Permeameter Model K-670.
[b] 1 cm/sec = 2.12×10^{4} gpd/ft^2.

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Printed by authority of the State of Illinois (3,000/1980)

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